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REINVESTIGATION OF OPTIMAL DURATION OF VO_2MAX TESTING

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ABSTRACT

REINVESTIGATION OF OPTIMAL DURATION OF VO_2MAX TESTING. **Astorino TA, Rietschel JC, Tam PA, Taylor K, Johnson SM, Freedman TP, Sakarya CE. JEP**online. 2004;7(6):1-8. The traditional 8-12 min criterion followed as the optimal duration of maximal oxygen uptake (VO_2max) testing was developed on only five older men during treadmill walking. However, it is unknown if this criterion is applicable to a larger, younger, and more diverse group of subjects completing incremental treadmill running. The primary aim of the study was to test the validity of this criterion in a large, young, and heterogeneous population. After a familiarization trial, subjects (16 men and 10 women) completed incremental treadmill VO_2max tests of approximately 6 (short=S), 10 (medium=M), and 14 (long=L) min duration on separate days. Treadmill speed was self-selected and remained constant during all trials, but grade increment was manipulated to induce fatigue in the desired duration. During exercise, breath-by-breath gas exchange data and heart rate (HR) were continuously obtained. Blood samples were obtained post-exercise to measure blood lactate concentration ([La]). VO_2max was significantly lower in L (3.4±0.8 L/min) versus M (3.6±0.8 L/min). Compared to M, VCO_2max and RERmax were significantly lower in L. Maximal [La] and HR were significantly lower in L. These data confirm that incremental treadmill protocols of approximately 7–10 min duration optimize VO_2max, and longer protocols (>13 min) significantly reduce VO_2max, VCO_2max, and HRmax. This duration of incremental exercise may be applicable for testing young people including women, recreational athletes, and the endurance-trained.

Key Words: Treadmill running, Lactate, Fatigue, Maximal oxygen uptake

INTRODUCTION

Maximal oxygen uptake (VO_2max) is a fundamental measure of exercise physiology. It is an index of cardiovascular performance as well as a measure of aerobic capacity (1). Early work by Hill and colleagues (2) developed the concept of VO_2max by requiring men to run at various speeds during which gas exchange data were obtained every three minutes. However, these and other measurements of VO_2max obtained in classical studies (3-5) were obtained via discontinuous exercise protocols that are rather inappropriate for precise determinations of VO_2max. Despite the widespread completion of VO_2max testing in clinical, fitness, and research facilities, an optimal duration of incremental exercise yielding a precise measurement of VO_2max in a wide variety of individuals, including young men and women who are sedentary, recreationally active, or endurance-trained, has yet to be identified.

Early investigation (3) requiring 15 men (age equal to 32.0 yr) to complete each of the Bruce, Balke, and Taylor protocols three times over a 9-week period demonstrated that VO_2max is 7-10 % higher in response to the Taylor running protocol (duration equal to 12 min) compared to incremental walking protocols. Pollock et al. (6) administered VO_2max protocols including the Balke test, Bruce Protocol, and Ellestad and Astrand running protocols to 51 healthy men (age equal to 40.5±5.3 yr). Data revealed that VO_2max is significantly higher in response to the Astrand protocol (41.8±6.7 mL/kg/min, duration equal to 7.8±1.1 min) versus the Balke test (39.4±5.9 mL/kg/min, duration equal to 16.9±3.8 min). These early studies suggest that treadmill walking/running protocols of approximately 8–12 min elicit the highest values of VO_2max compared to maximal walking protocols, but the suitability of this duration in younger subjects completing treadmill running has yet to be clarified.

To identify the optimum protocol for graded exercise testing, subsequent research (1) required 12 healthy men to complete various incremental protocols on a treadmill and cycle ergometer. Data demonstrated that durations of 10.6, 11.4, and 15.1 min result in the highest value of VO_2max, yet this was obtained in a subset of only five healthy men (mean age and VO_2max equal to 36.0±9.7 yr and 52.0±8.4 mL/kg/min, respectively) completing incremental treadmill walking. In addition, maximal ventilation, VCO_2, and oxygen pulse were significantly different ($p<0.05$) across treadmill protocols ranging from 7.0-26.4 min. More recent data (7) in nine healthy, recreationally active men and women (mean age and VO_2max equal to 27.0±4.0 yr and 4.1±1.1 L/min, respectively) completing maximal treadmill running revealed no difference in VO_2max among tests of 6 and 12 min duration, although maximal cardiac output and stroke volume were significantly different among the protocols.

In recreational athletes, it is possible that incremental exercise lasting less than 8 min may underestimate VO_2max due to greater glycolytic contribution to ATP provision and enhanced fast-twitch (FT) recruitment. In contrast, incremental exercise greater than 14 min may underestimate VO_2max due to potential onset of boredom and local muscle fatigue. In endurance-trained populations, shorter protocols may reveal similar values for VO_2max compared to longer protocols, as athletes tend to have a more developed anaerobic capacity to tolerate the high work rates consequent with near-maximal exercise. However, differences in maximal heart rate (HR), respiratory exchange ratio (RER), rating of perceived exertion (RPE), and blood lactate concentration ([La]) between long and short protocols may indicate greater relative physiological perturbation and thus augmented physical stress during incremental exercise.

In regards to the 8–12 min criterion developed as the optimal duration of incremental exercise (1), it seems unwise to recommend this duration when this guideline was developed from treadmill testing of a small sample of older men. The results from such a sample are hardly generalizable to the majority of subjects completing tests of maximal oxygen uptake today in the research setting. Therefore, the primary purpose of the present investigation was to compare VO_2max, gas exchange data, and [La] across three incremental exercise protocols of varying duration. Consequently, a relatively large number of subjects varying in fitness and gender were recruited to confirm the validity of this criterion in a younger and more heterogeneous population.

METHODS

Subjects

A group of 27 (16 men and 11 women) college students and individuals from the university area participated in the present study. However, one subject failed to complete her final trial, so data are reported for 26 subjects. Eleven men (VO_2max$\geq$60 mL/kg/min) were runners on the university track and cross-country teams; whereas, the remaining 16 subjects were recreationally active men and women. Initially, subjects provided their written informed consent and filled out a health/history questionnaire to confirm that they were free of any condition that could prevent them from exercising to VO_2max.

Procedures

Subjects completed a familiarization trial during which they exercised to volitional fatigue on a motor-driven treadmill (Quinton Instruments Q55, Series 90, Seattle, WA) and became acclimated to the simultaneous acquisition of gas exchange data. During this trial, subjects ran at a self-selected speed and grade increment was increased approximately 1 % every minute, with the aim to induce fatigue in approximately 10 min. It was emphasized that subjects exercise to volitional fatigue. If subjects did not attain VO_2max confirmed by standard criteria (8), the familiarization trial was repeated, or the subject was eliminated from participation in the study. Similarly, if the duration did not fall between 8–14 min, the test was repeated on a separate day with manipulation of treadmill grade increment to induce fatigue in the desired duration. However, all subjects attained VO_2max during this trial. During testing, breath-by-breath gas exchange data (SensorMedics Vmax 29C, Yorba Linda, CA) and heart rate (Polar Electro Inc., Woodbury, NY) were continuously obtained.

Subjects were instructed to follow specific pretest guidelines prior to each visit to the laboratory, which included no alcohol, caffeine, or smoking for 48 h, and no strenuous exercise for 12 h prior to testing. In addition, subjects maintained a record of their exercise and dietary regimen during the completion of all testing. All experimental procedures were approved by the Human Research Review Board of the university.

Treadmill Protocols

Subjects completed three additional VO_2max tests, separated by at least 48 h, of varying duration on the treadmill. All tests were performed at the same time of day for each subject. The order of testing was assigned to subjects based on a Latin Squares Design (9). Based on maximal treadmill grade obtained from the familiarization trial, grade increment per minute was individualized for each subject to induce fatigue in approximately 6, 10, and 14 min, respectively. Treadmill speed was self-selected by all subjects and was constant for all tests. If a subject failed to complete a VO_2max test in the assigned duration, the subject returned to the laboratory and treadmill grade increase was adjusted to elicit the desired duration of incremental exercise. Subjects and all researchers with the exception of those operating the treadmill were unaware of the specific protocol to be administered that day. Pilot testing revealed a coefficient of variation for VO_2max equal to 3.5 %.

Gas Exchange Data

During exercise, subjects expired through a plastic mouthpiece and low-resistance valve into tubing connected to a mixing chamber. Ventilation was measured by inspired air-flow through standard gas analyzers. These analyzers were calibrated prior to each test to room air and medically-certified calibration gases (26 %O_2 and 74 %N_2, 16 %O_2 and 4 %CO_2, respectively). Using a 3 L syringe, volume of flow was also calibrated prior to each experimental trial. Measurements of ventilation (V_E), oxygen uptake (VO_2), carbon dioxide production (VCO_2), respiratory exchange ratio (RER), and respiratory rate (RR) were obtained breath-by-breath throughout exercise. Heart rate was recorded during exercise by telemetry. After 2–5 min of resting gas exchange data, exercise was started, and the subject completed incremental exercise in the assigned duration. Subjects were instructed to exercise to volitional fatigue. The test was terminated when the subject grabbed the handrails and straddled the treadmill.

VO_2max was confirmed by incidence of a plateau in VO_2 at VO_2max ($\Delta VO_2 \leq 60$ mL/min at VO_2max and the closest neighboring data point) and maximal RER > 1.10. Due to the absence of any generally accepted criteria for assessing and quantifying VO_2max and a VO_2 plateau, these criteria were developed in 150 subjects of varying fitness, age, and gender from prior testing in our laboratory (Astorino, unpublished data). Maximal HR within 10 b/min of age-predicted maximal HR (220–age) was also used as a secondary criterion to confirm incidence of VO_2max. All subjects except one met the first two criteria. Rating of perceived exertion (RPE) (10) was obtained every minute during exercise.

Blood Sampling

Fingertip blood samples (25 μL) were obtained at rest and immediately post-exercise during each trial. Blood lactate concentration ([La]) was measured in duplicate using a lactate analyzer (YSI Model #1500, Yellow Springs, OH). This analyzer was calibrated to a 5 mM standard prior to each experimental trial.

Due to technical difficulties, [La] data were obtained for only 16 (nine male runners, seven recreational athletes) subjects.

Statistical Analyses

All data are presented as mean ± standard deviation (SD) and were analyzed using GraphPad Prism Version 3.0 (San Diego, CA). A one-way analysis of variance with repeated measures was used to examine differences in gas exchange parameters, maximal HR, and [La] across the various VO_2max tests. If a significant F ratio was obtained, Tukey's post hoc test was used to locate significant differences between means. Statistical power was calculated to ensure that the experimental design had sufficient ability to detect differences in VO_2max among protocols. With a sample size equal to 20, statistical power equal to 0.80, and standard deviation equal to 0.112 L/min, we could detect a difference of 0.117 L/min using an unpaired, one-tailed t-test with significance set at 0.01. Statistical significance was set at 0.05.

RESULTS

Demographic data consisting of mean age, height, weight, and VO_2max of all 26 subjects were 21.0±3.0 yr, 171.8±3.6 cm, 65.4±12.2 kg, and 54.8±10.2 mL/kg/min, respectively.

Because no differences in mean VO_2max across protocol were evident in our subsets of women or endurance-trained runners, data were pooled. All data for the 26 subjects are shown in Table 1. No difference in mean VO_2max was evident between S or M, yet VO_2max was significantly lower ($p<0.05$) in L. Figure 1 shows the VO_2 response versus time across protocols in a recreationally-active female. In this subject, VO_2max was higher in S (3.22 L/min) and M (3.24 L/min) compared to L (3.16 L/min). Differences in VO_2max across protocols are shown in Figure 2. Compared to L, VO_2max tended to be highest in S and M in all subjects irrespective of fitness level. Maximal VCO_2 and O_2pulse were significantly higher ($p<0.01$) in S and M compared to L. RER at VO_2max was highest ($p<0.05$) in response to S (1.19±0.07). As expected, maximal treadmill time and peak workload were significantly different ($p<0.05$) across protocol. Ventilation and respiratory rate (RR) at VO_2max were unaltered by protocol duration.

Table 1. Differences in gas exchange parameters between incremental Exercise protocols of different duration.

Parameter (Mean±SD)	*Short (S)*	*Medium (M)*	*Long (L)*
Duration (min)[a]	7.38±0.60	10.50±0.87	13.90±1.34
Speed (mi/h)	7.45±1.21	7.45±1.21	7.45±1.21
Grade (%)[a]	12.70±2.40	10.50±1.47	8.74±1.47
VO_2max (L/min)	3.56±0.83	3.58±0.83	3.45±0.79[c]
VCO_2max (L/min)[a]	4.24±1.05	4.12±1.00	3.89±0.88
$V_E$max (L/min)	126.0±27.40	125.0±28.20	121.0±24.90
O_2pulse (mL/beat)	19.00±4.61[d]	18.90±4.68 [d]	18.20±4.34
RER	1.19±0.07	1.15±0.06[b]	1.13±0.05[b]
RR (breaths/min)	56.30±6.64	58.40±6.37	58.10±7.16

a = significantly different ($p<0.05$) between protocols
b = significantly different ($p<0.05$) from S
c = significantly different ($p<0.05$) from M
d = significantly different ($p<0.05$) from L
RER = respiratory exchange ratio, RR = respiratory rate.

HR at VO_2max was significantly lower ($p<0.05$) in S (187.0±9.4 b/min) compared to M (190.0±8.9 b/min) and L (190.0±8.3 b/min). Blood [La] in L (8.5±1.4 mmol/L) was significantly lower ($p<0.05$) versus M (9.9±1.7 mmol/L) and S (10.1±2.0 mmol/L).

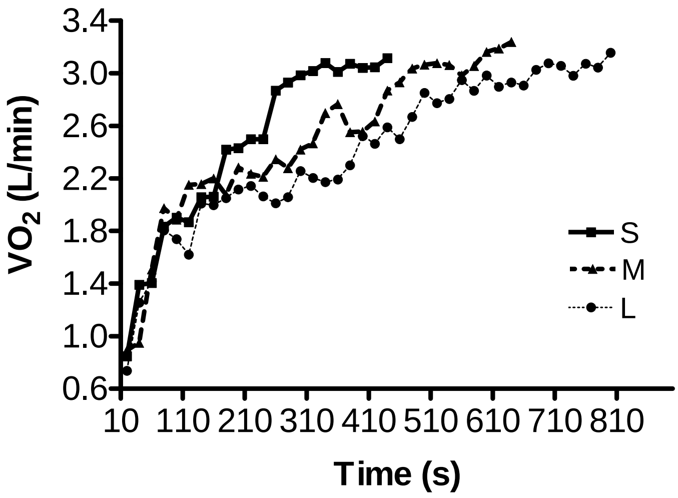

Figure 1. VO_2 response to various duration of incremental exercise in subject 26.

DISCUSSION

The present investigation was undertaken to examine the validity of the 8–12 min criterion previously established as the optimal duration of VO_2max testing (1). This duration has been extensively used for years despite the fact it was developed from treadmill testing of only five older, healthy men. Our results in 26 young subjects varying in gender and fitness level demonstrated that VO_2max is significantly lower when treadmill exercise ensues for longer than the recommended 8-12 min duration. In addition, maximal VCO_2, RER, and [La] were significantly higher in response to incremental exercise less than 8 min, which suggests a greater metabolic acidosis in shorter incremental protocols. These data support the continued use of the 8-12 min criterion, and extend its application to testing of younger subjects, specifically women, recreational athletes, and endurance-trained men.

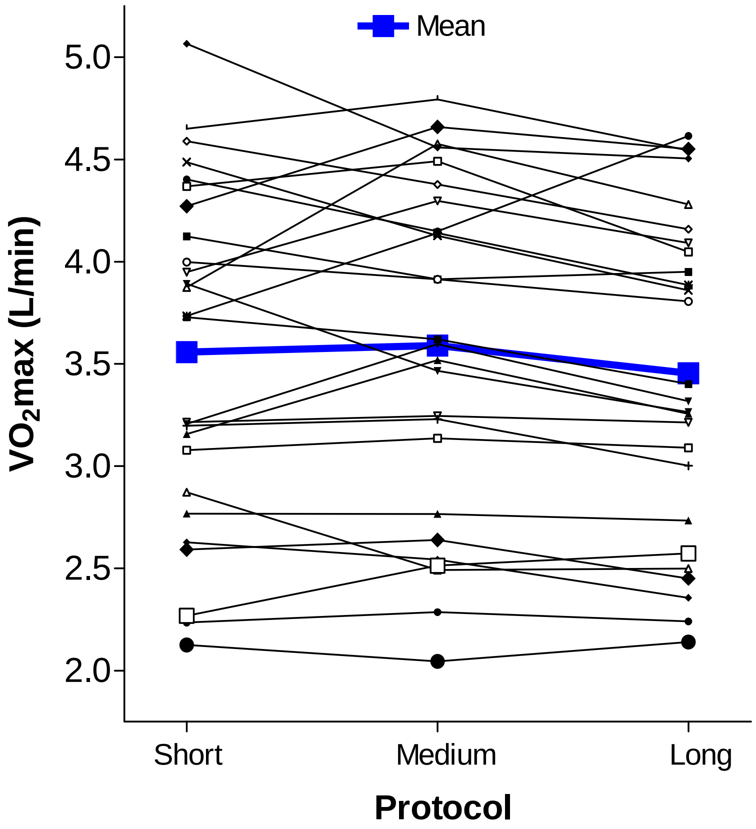

Figure 2. Intra-subject change in VO_2max with various durations of incremental exercise.

Our findings are similar to data obtained in healthy, older (age equal to 39.0 yr) men (1). In this study, 12 men completed incremental treadmill walking and cycle ergometry during which work rate increment was altered to manipulate time to fatigue. A subset of five men (age equal to 36.0 yr, ranging from 28-54 yr) with a mean VO_2max equal to 52.0 mL/kg/min completed multiple incremental treadmill tests of 7.0-26.4 min duration on separate days to assess maximal metabolic and cardiopulmonary function. Results demonstrated that incremental exercise of 10.6, 11.4, and 15.1 min optimized VO_2max (3.89, 3.94, and 3.88 L/min, respectively) while shorter protocols (7.0 min) significantly reduced VO_2max (3.68 L/min). This led the authors to conclude that a duration of incremental exercise equal to 10±2 min optimizes VO_2max. VO_2max was also lower in response to incremental exercise lasting 26.4 min (3.77 L/min), yet the small sample size eliminated incidence of statistically significant findings. In contrast, our data from a larger group of subjects varying in age, gender, and fitness revealed that VO_2max is significantly lower (4–5 %) when incremental exercise lasts longer than

13 min. The finding of a significantly lower VO_2max in longer protocols was also demonstrated in 51 endurance-trained and sedentary men (6) and in 15 healthy men (3). However, subjects in these studies were required to complete the Balke and Bruce exercise protocols that require primarily walking at a steep and ultimately uncomfortable grade. Other data, however, revealed no differences in VO_2max during running protocols of different duration in adults (7,11) and children (12), yet sample size was less than ten subjects.

When comparing maximal cardiovascular performance across different protocols, it is essential that subjects attain VO_2max. In the present study, a familiarization trial was completed by all subjects prior to testing. This enabled subjects to become comfortable with treadmill running as well as exercise to volitional fatigue. In addition, subjects were young, active, very motivated, and were verbally encouraged to run until exhaustion during all testing. A plateau in VO_2 ($\Delta VO_2 \leq 60$ mL/min) and a maximal RER>1.10 were used in the present study to confirm that VO_2max was attained. All subjects except one met these criteria. Consequently, it was assumed that subjects attained VO_2max.

VO_2max was 4 % lower in L versus M and S (Table I). This result is physiologically meaningful, as the test-retest reliability of VO_2max testing has been reported to be 2–6 % in adults (13) and 3–6 % in children (12). In 15 healthy men (3), a coefficient of variation equal to 4.1 % (range 0.8–9.3 %) was reported for repeated trials of the Taylor running protocol, similar to data from Howley and colleagues (14) in response to ten measurements of VO_2max in one subject. In the present study, pilot testing revealed a coefficient of variation equal to 3.5 % for VO_2max and time to fatigue across repeated days of treadmill testing in three subjects.

Potential factors explaining the lower VO_2max in L in the present study include alterations in HR, cardiac output (Q), stroke volume (SV), arterio-venous difference (a-$vO_2\Delta$), and body temperature. HR was significantly lower ($p<0.05$) in S versus L and M. A previous report (7) concluded that maximal Q and SV are significantly lower in response to long (12.4 min) versus short (6.7 min) incremental protocols. In fact, these authors stated that Q is maximized during protocols of 5–9 min duration. In regards to a-$vO_2\Delta$, this study (7) demonstrated no difference in maximal a-$vO_2\Delta$ between short and long protocols. During longer protocols, core temperature may rise to a greater degree, causing enhanced peripheral vasodilation and thus lower venous return and SV. In addition, O_2 pulse was significantly lower in L versus M (Table 1), suggesting reduced VO_2 per heartbeat. Thus, during longer protocols a compromised O_2 delivery due to decrements in SV and Q may explain the lower VO_2max observed in the present study.

Alternatively, failure to reach the same maximal workload can also explain the lower VO_2max in response to L (treadmill time equal to 13.9±1.3 min). Subjects attained a significantly lower grade at VO_2max in L (8.7±1.5 %) compared to S (12.7±2.4 %) and M (10.5±1.5 %). Inserting maximal treadmill speed and grade into the ACSM metabolic equation for treadmill running (8), this represents a 5 % lower VO_2max in L (59.1 mL/kg/min) compared to M (62.3 mL/kg/min), similar to the difference observed in the present study.

At VO_2max, VCO_2 and RER were significantly lower in L compared to M (Table 1). Despite the fact that ventilation at VO_2max was similar across protocols, these findings suggest a lower non-metabolic production of CO_2 during longer protocols. Maximal [La] was significantly lower in L versus M and S, suggesting reduced lactate production or enhanced clearance in protocols with a more gradual increase in work rate. For example, the average grade increment per minute in S was equal to approximately 1.7 %/min, versus 1.0 % and 0.6 %/min, respectively, in M and L. The slower increase in treadmill grade consequent with L must have induced both a smaller contribution of glycolysis and phosphocreatine to energy metabolism as well as an attenuated recruitment of type II fibers, consequently supporting the reduced [La]. Subjects expressed greater leg and ventilatory discomfort in response to S versus L. In the future, research is warranted to examine activities of lactate and pyruvate dehydrogenase and their role in regulating blood lactate concentration during different incremental protocols.

The practical significance of these findings lies in the widespread completion of VO_2max testing in research, health, sport, and fitness settings. A precise estimate of VO_2max must be used when prescribing exercise regimens based on %VO_2max to exercisers in the fitness or rehabilitation setting. Second, it is evident that chronic endurance training increases VO_2max, and that VO_2max plays a role in classifying endurance performance. Third, protocol duration should be tolerable for the subject. Lastly, to better compare VO_2max across studies, it would be convenient if all scientists adapted this 8-12 min criterion when administering incremental exercise tests to subjects.

CONCLUSIONS

Our results in 26 young subjects varying in gender and fitness support use of the 8–12 min duration of incremental exercise, as VO_2max was significantly higher in response to incremental protocols of approximately 7–10 min duration. Maximal HR, RER, VCO_2, O_2 pulse, and [La] were also significantly different between protocols. Changes in muscle temperature, O_2 delivery, and blood acid/base balance may explain the lower VO_2max observed in response to longer protocols. The 8-12 min criterion can be applied to young women, endurance-trained athletes, and recreational exercisers completing incremental treadmill running, yet its use during cycle ergometry remains to be investigated.

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REFERENCES

1. Buchfuhrer MJ, Hansen JE, Robinson TE, Sue DY, Wasserman K, Whipp BJ. Optimizing the exercise protocol for cardiopulmonary assessment. ***J Appl Physiol*** 1983;55:1558-64.
2. Hill AV, Lupton H. Muscular exercise, lactic acid, and the supply and utilization of oxygen. ***Q J Med*** 1923;16:135-71.
3. Froelicher VF, Brammell H, Davis G, Noguera I, Stewart A, Lancaster MC. A comparison of three maximal treadmill protocols. ***J Appl Physiol*** 1974;36:720-5.
4. Mitchell JH, Blomqvist G. Maximal oxygen uptake. ***N Engl J Med*** 1973;284:1018-22.
5. Taylor HL, Buskirk E, Henschel A. Maximal oxygen intake as an objective measure of cardiorespiratory performance. ***J Appl Physiol*** 1955;8:73-80.
6. Pollock ML, Bohannon RL, Cooper KH, Ayres JJ, Ward A, White SR. et al. A comparative analysis of four protocols for maximal treadmill stress testing. ***Amer Heart J*** 1976;92:39-46.
7. McCole SD, Davis AM, Feuger PT. Is there a disassociation between maximal oxygen consumption and maximal cardiac output? ***Med Sci Sports Exerc*** 201;33:1265-9.
8. American College of Sports Medicine. **Guidelines for exercise testing and prescription**. Philadelphia, PA: Lippincott, Williams, & Wilkins, 2000, p.303.
9. Keppel G. ***Design and analysis: A researcher's handbook***. London: Prentice Hall, 1983.
10. Borg GAV. Psychophysical bases of perceived exertion. ***Med Sci Sports Exerc*** 1982;14:377-81.
11. Stamford BA. Step increment versus constant load tests for determination of maximal oxygen uptake. ***Eur J Appl Physiol*** 1976;35:89-93.
12. Paterson DH, Cunningham DA, Donner A. The effect of different treadmill speeds on the variability of VO_2max in children. ***Eur J Appl Physiol*** 1981;47:113-22.
13. Katch VL, Sady SS, Freedson P. Biological variability in maximum aerobic power. ***Med Sci Sports Exerc*** 1982;14:21-5.

14. Howley ET, Bassett DR, Welch HG. Criteria for maximal oxygen uptake: review and commentary. ***Med Sci Sports Exerc*** 1995;27:1292-1301.