ORIGINAL ARTICLE

Indirect estimation of VO_2max in athletes by ACSM's equation: valid or not?

Koutlianos N[1], Dimitros E[1], Metaxas T[2], Deligiannis AS[1], Kouidi E[1]

[1]Sports Medicine Laboratory,
[2]Laboratory of Ergophysiology-Ergometry,
Department of Physical Education & Sport Science, Aristotle University of Thessaloniki, Thermi, Greece

Abstract

Aim: The purpose of this study was to assess the indirect calculation of VO_2max using ACSM's equation for Bruce protocol in athletes of different sports and to compare with the directly measured; secondly to develop regression models predicting VO_2 max in athletes.

Methods: Fifty five male athletes of national and international level (mean age 28.3 ± 5.6 yrs) performed graded exercise test with direct measurement of VO_2 through ergospirometric device. Moreover, 3 equations were used for the indirect calculation of VO_2max: a) VO_2max = (0.2 · Speed) + (0.9 · Speed · Grade) + 3.5 (ACSM running equation), b) regression analysis model using *enter* method and c) *stepwise* method based on the measured data of VO_2. Age, BMI, speed, grade and exercise time were used as independent variables.

Results: Regression analysis using *enter* method yielded the equation (R=.64, standard error of estimation [SEE] = 6.11): VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$) = 58.443 - (0.215 · age) - (0.632 · BMI) - (68.639 · grade) + (1.579 · time) while *stepwise* method (R = .61, SEE = 6.18) led to: VO_2max ($ml \cdot kg^{-1} \cdot min^{-1}$) = 33.971 - (0.291 · age) + (1.481 · time). The calculated values of VO_2max from these regression models did not differ significantly from the measured VO_2max ($p>.05$). On the contrary, VO_2max calculated from the ACSM's running equation was significantly higher from the actually measured value by 14.6% ($p <.05$).

Conclusions: In conclusion, it seems that ACSM's equation is not capable of accurately predicting VO_2max in athletes aged 18-37 years using Bruce protocol. Only the regression models were correlated moderately with the actually measured values of VO_2max. Hippokratia 2013, 17, 2: 136-140

Keywords: VO_2max prediction, running equation, metabolic equivalent, exercise testing, cardiorespiratory fitness

Corresponding author: Dr Nikolaos Koutlianos, 75 Loutron Str, 57200 Lagadas, Greece, tel/fax: +302310992188, e-mail: koutlian@phed.auth.gr

Introduction

Maximal oxygen consumption (VO_2max) is defined as the ability to transport and consume oxygen during exhausted work and is related to cardiorespiratory fitness[1]. The American College of Sports Medicine (ACSM) has published several metabolic equations for the indirect estimation of VO_2max while walking, running, and stepping as well as for leg and arm ergometers[2].

In the laboratory setting, the most accurate way to assess VO_2max is undoubtedly via applying a maximal graded exercise test (GXT) performed to volitional exhaustion on a motorized treadmill or cycle ergometer while expired air is analyzed continuously by gas analyzers[3,4]. However, equipment costs and staff training limit direct measurement mainly to research and few clinical settings[5]. Thus, the need for an accurate prediction of the VO_2 with the use of various equations is considered necessary. The equations can be performed according to: work information (speed, grade, work rate, step rate) or following calculations of appropriate work.

There are several exercise treadmill protocols for the prediction of VO_2max. Current evidence suggests that in order to elicit the VO_2max of apparently healthy individuals, continuous treadmill tests should generally last between 5 and 26 minutes. This is dependent on the basis that short tests are preceded and that treadmill grades do not exceed 15%[6]. The running equation of ACSM is only valid with steady state exercise and is designed for speeds greater than 5.0 mph (134 $m \cdot min^{-1}$)[2].

In the literature, the majority of studies have developed several regression models for the prediction of VO_2max based on a variety of maximal treadmill exercise tests[2,7,8]. Additionally, the indirect estimation of multiple equivalents (METs) in the majority of the commercially available software of exercise test units is calculated from the ACSM running equation and it is applied in many cardiovascular centers and sports medicine labs even when using interval protocols on the treadmill. The degree of error in estimating aerobic capacity in the stress test setting is not well characterized and from our knowledge there is no study examining the accuracy of the ACSM running equation using the Bruce protocol in a specific population such as athletes although it is still widely used. The introduction of ventilatory expired gas analysis into traditional stress test procedures led to the direct measurement of VO_2. Despite this, estimating than directly measuring VO_2 remains a very common clinical standard in many stress-testing laboratories assessing exercise-trained subjects for cardiovascular screening. Thus, the aim of this study was to evaluate the accuracy of the indirect VO_2max measurement using the ACSM's running equation for the Bruce protocol in athletes of different sports in comparison with the directly estimated. Additionally, a secondary goal was the prediction of VO_2max using models of regression analysis.

Materials and Methods

Subjects

Study participants included 55 male athletes of different sports (soccer, n=15; basketball, n=13; cycling, n=7; volleyball, n=7; body-building, n=4; weightlifting, n=3; wrestling, n=3 and tae-kwon do, n=3). The physical and anthropometric characteristics of the subjects are listed in Table I. All subjects had a minimum of 3 training sessions per week and they were competing at national and international level. Before the study, subjects provided informed consent for their participation. The study protocol was in agreement with the guidelines of the Ethics Committee of the Aristotle University of Thessaloniki.

Pretesting Procedures

All subjects underwent a noninvasive cardiovascular screening, before exercise testing, in accordance with the recommended standards[9]. The height was measured to the nearest 0.5 cm using a stadiometer (KDS, Kyoto, Japan) and the weight to the nearest 0.1 kg on a medical-scale grade (Seca, Hamburg, Germany). All subjects were asked to avoid drinking any caffeinated and alcoholic beverages or using any ergogenic aids at least two days before the experimental session.

VO_2max direct measurements

All participants performed a maximal exercise test using a Trackmaster treadmill. For the purpose of the study the treadmill was calibrated in order to ensure the accuracy of grade and speed. Subjects exercised to exhaustion using Bruce protocol. All athletes did not use the handrails. The electrocardiogram was monitored continuously during the test (CH-2000, Cambridge Heart Co., USA). The VO_2max was measured via an ergospirometric device based on breath-by-breath gas analyzing system (Ultima Series, MedGraphics, USA). Prior to testing, a pneumotachograph was calibrated using a 3.0 L-syringe at various flow rates. Thereafter, oxygen and carbon dioxide analyzers were calibrated with known gas mixture according to the specifications of the manufacturer. The following exercise test criteria were used for the achievement of VO_2max:

1. Leveling off (plateau) of oxygen uptake with an increase of work rate[10].

2. Respiratory exchange ratio (VCO_2/VO_2) greater than 1.10[11].

3. Achievement of 90% of the age-adjusted estimate of maximal heart rate[12].

In addition, the following parameters were recorded from the cardiorespiratory exercise test: the duration of the test, the maximal value of $METs_{max}$ both by the ergospirometer and the exercise testing software unit using the Bruce protocol, the maximal pulmonary ventilation (VE_{max}), the maximal heart rate (HR_{max}), and the respiratory exchange ratio (RER).

VO_2max indirect calculations

We hypothesized that other equations except from the ACSM's metabolic equation might be accurate for the prediction of VO_2max. Thus, overall the VO_2max was calculated based on the following metabolic calculations:

1. ACSM equation: $VO_2max = (0.2 \cdot S) + (0.9 \cdot S \cdot G) + 3.5$ (equation A)[2]

S: speed; G: grade

2. VO_2max was estimated using regression models using enter (equation B) and stepwise (equation C) methods.

Additionally, using the ACSM equation, the subjects had to complete at least one minute of each stage in order to be awarded with the full estimated metabolic equivalents value.

Statistical analyses

Statistical analyses were performed using the PASW statistics for Windows version 18 (SPSS Inc., Chicago, Illinois, USA). All data were expressed as mean values and standard deviation (SD). Age, BMI, speed, grade and exercise time were served as independent variables in multiple linear regression analysis, using both *enter* and *stepwise* methods to predict measured VO_2max. *Enter* is a method in which all predictors are forced into the model simultaneously. This method relies on good theoretical reasons for including the chosen predictors, but the experimenter makes no decision about the order in which variables entered. In the *stepwise* method, decisions about the order in which predictors are entered into the model are based on a purely mathematical criterion. The computer then searches for the predictor that best predicts the outcome variable by selecting the predictor that has the highest simple correlation with the outcome. If this predictor significantly improves the ability of the model to predict the outcome, then this predictor is retained in the model and the computer searches for a second predictor. The criterion used for selecting this second predictor is that it is the variable that has the largest semi-partial correlation with the outcome[13]. Changes of variables within groups were evaluated by the Student's *t*-test for paired data. For the estimation of the relationship between the measured and predicted values of VO_2max, as calculated from the three equations, Pearson correlation was used. Level of significance was set at $p<.05$.

Results

Athletes' physical characteristics are reported in Table 1. The cardiorespiratory data during rest and maximal exercise test are presented in Table 2.

All the subjects ultimately completed at least one minute of the fifth stage ensuring that they reached a running

Table 1: Physical and anthropometric data of athletes (mean ± SD).

	mean ± SD
Age (years)	28.3 ± 5.6
Training experience (years)	15.0 ± 10.1
Height (cm)	181.0 ± 0.1
Weight (kg)	81.1 ± 10.5
Body Mass Index (kg·m^{-2})	24.7 ± 2.9

SD: standard deviation.

Table 2: Cardiorespiratory data at rest and maximal exercise test (mean ± SD).

	Resting	Maximal Exercise
HR (beats·min^{-1})	69.7 ± 7.0	183.5 ± 12.7
VO_2 (ml·kg^{-1}·min^{-1})	6.0 ± 2.2	46.1 ± 7.6
VE (l·min^{-1})	13.6 ± 4.0	120.3 ± 21.4
RER	0.85 ± 0.1	1.21 ± 0.14
METS^a	1.7 ± 0.62	13.1 ± 2.2
METS^b	-	17.6 ± 1.2
Time (min)	-	14.1 ± 1.3

METS^a: Actually measured values of METS as calculated from the ergospirometry, METS^b: Indirect estimation of METS as calculated from the CH-2000 stress test unit on Bruce protocol according to the equation METs = [(0.1 · speed m·min^{-1}) + (1.8 · speed m·min^{-1} · fraction grade) + 3.5 ml·kg^{-1}·min^{-1}] / 3.5[2], SD: standard deviation.

speed at the end of the test since the running economy might be different between fast walking and running.

Multiple linear regression analysis using the *enter* method yielded the following prediction equation (B): VO_2max (ml·kg^{-1}·min^{-1}) = 58.443 - (0.215 · age) - (0.632 · BMI) - (68.639 · grade) + (1.579 · time) (R =.64, SEE = 6.11). The model was statistically significant ($p<.05$) explaining 40.7% (R^2=.407) of the variance of measured VO_2max. According to standardized β-weights (Table 3), age explained the largest amount of variance of VO_2max.

Stepwise regression analysis generated the following equation (C): VO_2max (ml·kg^{-1}·min^{-1}) = 33.971 - (0.291 · age) + (1.481 · time) (R=.61, SEE=6.18). Both age and exercise time, as predictor variables for VO_2max, were statistically significant ($p<.05$) explaining the 36.8% (R^2=.368) of the variance of VO_2max. The unstandardized coefficients, *t* statistics, and *beta* coefficients for each independent variable are shown in Table III. There were no collinearities in both models of regression analysis since the values of the variance inflation factor (VIF) and the tolerance (1/VIF) for all the predictors in both methods were <4 and >0.2, respectively.

The differences between the values of VO_2max, as they were calculated from the metabolic equations, are demonstrated in Table 4. Specifically, the calculated value of VO_2max based on equation A was significantly higher compared to the actually measured VO_2max by 14.6% ($p<.05$). Thus, the equation A was poorly, but nevertheless

Table 3: Multiple regressions analyses results for predicting VO_2max (ml·kg^{-1}·min^{-1}).

	Enter				Stepwise			
	β	*t-value*	*b-weight*	p	β	*t-value*	*b-weight*	p
Constant	58.44	2.32	-	.024	33.97	3.10	-	.003
Age	-0.215	-2.63	-0.36	.011	-0.291	-4.12	-0.48	.000
BMI	-0.632	-1.79	-0.24	.080	-	-	-	-
Grade	-68.639	0.69	-0.07	.687	-	-	-	-
Exercise time	1.579	0.13	0.26	.132	1.481	2.08	0.24	.043

Table 4: Differences between measured and predicted values of VO_2max (mean ± SD).

VO_{2max}	mean ± SD (ml·kg^{-1}·min^{-1})	df (%)	*p*
Measured VO_{2max}	46.09±7.63	-	-
A	52.83±2.81*	14.6	.000
B	46.08±4.87	0.02	.994
C	46.08±4.63	0.02	.995

*$p<.05$ vs measured VO_2max, A=ACSM's running equation[2], B= Regression equation (*enter* method), C= Regression equation (*stepwise* method), SD: standard deviation.

significantly correlated with the measured VO_2max, while *enter* and *stepwise* regression equations were moderately correlated with the measured VO_2max. Particularly, the correlation coefficients between the actually measured and the equation-based predicted values of VO_2max were 0.27 (p=0.043) for equation A and 0.64 ($p<0.001$) and 0.61 ($p<0.001$) for equations B and C, respectively.

Discussion

The main finding of the study was that the ACSM's running equation overestimates the VO_2max values when assessed in athletic population. On the contrary, the regression-based equations were significantly correlated with the actually measured VO_2max.

Measurement of VO_2max has ubiquitous outcomes in many fields of exercise science[14,15]. Thus, an increase of VO_2max is the most important demonstration for a training effect[14]. In clinical settings, VO_2max has also become the gold standard measure of cardiovascular fitness and exercise capacity[16]. Low cardiorespiratory fitness is a powerful and independent predictor of cardiac mortality in patients with chronic heart failure or hemodialysis patients[17-19]. On the contrary, an improvement of aerobic capacity following exercise training is associated with a lower risk of morbidity and mortality in these patients[20,21].

In a previous study, Foster et al[22], had suggested that individual characteristics may present significant impact on the estimation of VO_2. Even though the ACSM's equation was developed using highly fit male subjects or based on estimates[23,24], our data suggest that its use for predicting VO_2max in a group of athletes aged 18-37 yrs participating in various sport disciplines leads to inaccurate results. Particularly, ACSM's running equation overestimates the VO_2max values by 14.6% when assessed in athletes. Also, other studies have criticized the use of the ACSM's equation in adults[25]. This overestimation of the ACSM's equation in predicting VO_2max is most likely due, in part to its intended use for estimation during steady state exercise, which makes it inappropriate for use with graded stress testing of any age group[5,26]. Furthermore, many studies have shown that trained and elite athletes exhibit better running economy than untrained and amateur or recreational athletes, respectively[27]. These differences in running economy and energy expenditure have been attributed to several biomechanical, metabolic and neuromuscular factors such as metabolic adaptations of the muscular cell, the ability of the muscles to store and release elastic energy and more efficient mechanics such as improved running technique, leading to less expended energy on braking forces and minimized vertical oscillation[28].

Physical activity levels may be an independent predictor of VO_2max in healthy adults, following sex and age in order of significance[7]. In absence of specific physical activity recordings in our study and comparisons between sex, the age was found to be a significant predictor of VO_2max in both *enter* and *stepwise* regression equations. In the present study, the age factor was more effective than BMI, grade and exercise time using the *enter* method and more effective than exercise time when using *stepwise* method, while BMI, speed and grade were excluded from this model analysis. Peterson et al[5], observed a 0.20 increase in R^2 when adding gender, age, BMI and activity levels to a model that originally included just the "traditional" test variables of treadmill: grade and speed.

Age is considered to be an important variable when estimating VO_2max across a wide chronological range[14]. George et al[29] used a maximal graded exercise test to predict VO_2max in 18-65 aged adults and they concluded that the age seems to be more effective at predicting VO_2 max than gender and BMI, but not as effective as treadmill speed and grade.

Peterson et al[14], also reported that there was a lack of significance for the exercise time as a predictor of VO_2max, due to the used Pieper protocol, suggesting that protocols utilizing large metabolic increments such as the Bruce protocol would make test duration a significant predictor of VO_2max. This observation is confirmed by our results using *stepwise* regression equation. Nevertheless, exercise time was not a strong predictor of VO_2max when using *enter* method in regression analysis.

The most common maximal GXT for the treadmill still remains the Bruce protocol that provides excellent accuracy and a standardized testing procedure for all participants[7]. The Bruce protocol has advantages and disadvantages and probably is not appropriate for predicting VO_2max in all populations due to the abrupt increase in exercise intensities which make it difficult for many individuals to complete[28]. Bruce et al[7,8], studied inherent physiologic differences between healthy, sedentary and diseased populations. In each population, a unique relationship of work load with VO_2 existed. On the other hand, the Bruce protocol requires all participants to advance from one stage to the next at the same speed and grade making it comparable between participants based on the same exercise intensity requirements. Also, total exercise time can be used by clinicians as a measured variable to accurately classify participants according to cardiorespiratory fitness or cardiovascular risk[1].

The limitations of the study mainly concern the size of the sample since a small number of athletes from eight different sport disciplines were recruited. Thus, it would have been advantageous to have included a randomly matched cohort of athletes from many different sports in order to quantify the VO_2max discrepancy under the also known limitation of the aggressive nature in workload adjustment of the Bruce protocol. Furthermore, the training characteristics might differ between the athletes' sport clubs in terms of frequency and intensity of the training load even in the same sport.

Conclusions

Our results indicated that the widely used ACSM's running equation performing the Bruce protocol in many sport centers is not accurately predicting VO_2max in athletes aged 18 - 37 years. Thus, it is verified that direct measurement of VO_2max in athletes should be preferred instead. Cardiopulmonary exercise testing is the only way to directly measure VO_2, but despite this, the estimation of exercise capacity based on equations will undoubtedly continue mainly due to cost effectiveness issues. In case of indirect estimation of maximal aerobic capacity, regression models in specific populations of different age and physical fitness with standard treadmill velocities and grades would be most efficient in predicting VO_2max. Further studies are encouraged to develop and examine precise regression models that accurately estimate VO_2max.

Conflicts of interest

None declared.

References

1. Bisi MC, Stagni R, Gnudi G. Automatic detection of maximal

oxygen uptake and ventilatory threshold. Comput Biol Med. 2011; 41: 18-23.
2. Glass S, Gregory B. ACSM's Metabolic Calculations Handbook. Lippincott Williams & Wilkins, Baltimore, 2007, 25-74.
3. Astorino TA, Willey J, Kinnahan J, Larsson SM, Welch H, Dalleck LC. Elucidating determinants of the plateau in oxygen consumption at VO2max. Br J Sports Med. 2005; 39: 655-660; discussion 660.
4. George JD, Paul SL, Hyde A, Bradshaw DI, Vehrs PR, Hager RL et al. Prediction of maximum oxygen uptake using both exercise and non-exercise data. Meas Phys Educ Exerc Sci. 2009; 13: 1-12.
5. Lee JM, Bassett DR Jr, Thompson D, Fitzhugh EC. Validation of the Cosmed Fitmate for prediction of maximal oxygen consumption. J Strength Cond Res. 2011; 25: 2573-2579.
6. Midgley AW, Bentley DJ, Luttikholt H, McNaughton LR, Millet GP. Challenging a dogma of exercise physiology: does an incremental exercise test for valid VO2max determination really need to last between 8 and 12 minutes? Sports Med. 2008; 38: 441-447.
7. Bruce RA, Kusumi F, Hosmer D. Maximal oxygen intake and nomographic assessment of functional aerobic impairment in cardiovascular disease. Am Heart J. 1973; 85: 546-562.
8. Bruce RA, Kusumi F, Niederberger M, Petersen JL. Cardiovascular mechanisms of functional aerobic impairments in patients with coronary heart disease. Circulation. 1974; 49: 696-702.
9. Corrado D, Pelliccia A, Bjørnstad HH, Vanhees L, Biffi A, Borjesson M, et al; Study Group of Sport Cardiology of the Working Group of Cardiac Rehabilitation and Exercise Physiology and the Working Group of Myocardial and Pericardial Diseases of the European Society of Cardiology. Cardiovascular pre-participation screening of young competitive athletes for prevention of sudden death: proposal for a common European protocol. Consensus Statement of the Study Group of Sport Cardiology of the Working Group of Cardiac Rehabilitation and Exercise Physiology and the Working Group of Myocardial and Pericardial Diseases of the European Society of Cardiology. Eur Heart J. 2005; 26: 516-524.
10. Howley ET, Basset DR Jr, Welch HG. Criteria for maximal oxygen uptake: review and commentary. Med Sci Sports Exerc. 1995; 27: 1292-1301.
11. Koutlianos N, Kouidi EJ, Metaxas TI, Deligiannis AP. Noninvasive cardiac electrophysiological indices in soccer players with mitral valve prolapse. Eur J Cardiovasc Prev Rehabil. 2004; 11: 435-441.
12. Gibson TM, Harrison MH, Wellicone RM. Evaluation of a treadmill work test. Br J Sports Med. 1979; 13: 6-11.
13. Field A. Discovering Statistics Using SPSS. SAGE publications, London, 2005, 160-161.
14. Bassett DR Jr, Howley ET. Limiting factors for maximum oxygen uptake and determinants of endurance performance. Med Sci Sports Exerc. 2000; 32: 70-84.
15. Levine BD. VO2max: what do we know, and what do we still need to know? J Physiol. 2008; 586: 25-34.
16. Fletcher GF, Balady GJ, Amsterdam EA, Chaitman B, Eckel R, Fleg J, et al. Exercise standards for testing and training: a statement for healthcare professionals from the American Heart Association. Circulation. 2001; 104: 1694-1740.
17. Wei M, Gibbons LW, Kampert JB, Nichaman MZ, Blair SN. Low cardiorespiratory fitness and physical inactivity as predictors of mortality in men with type 2 diabetes. Ann Intern Med. 2000; 132: 605-611.
18. Deligiannis A. Cardiac adaptations following exercise training in hemodialysis patients. Clin Nephrol. 2004; 61 Suppl1: S39-S45.
19. Kouidi E, Karagiannis V, Grekas D, Iakovides A, Kaprinis G, Tourkantonis A, et al. Depression, heart rate variability, and exercise training in dialysis patients. Eur J Cardiovasc Prev Rehabil. 2010; 17: 160-167.
20. Kokkinos P, Myers J, Kokkinos JP, Pittaras A, Narayan P, Manolis A, et al. Exercise capacity and mortality in black and white men. Circulation. 2008; 117: 614-622.
21. Kodama S, Saito K, Tanaka S, Maki M, Yachi Y, Asumi M, et al. Cardiorespiratory fitness as a quantitative predictor of all-cause mortality and cardiovascular events in healthy men and women: a meta-analysis. JAMA. 2009; 301: 2024-2035.
22. Foster C, Jackson AS, Pollock ML, Taylor MM, Hare J, Sennett SM, et al. Generalized equations for predicting functional capacity from treadmill performance. Am Heart J. 1984; 107: 1229-1234.
23. Balke B, Ware RW. An experimental study of physical fitness of Air Force personnel. U S Armed Forces Med J. 1959; 10: 675-688.
24. Dill DB. Oxygen cost of horizontal and grade walking and running on the treadmill. J Appl Physiol. 1965; 20: 19-22.
25. Cunha FA, Catalão RP, Midgley AW, Gurgel J, Porto F, Farinatti PT. Do the speeds defined by the American College of Sports Medicine metabolic equation for running produce target energy expenditures during isocaloric exercise bouts? Eur J Appl Physiol. 2012; 112: 3019-3026.
26. Marsh CE. Evaluation of the American College of Sports Medicine submaximal treadmill running test for predicting VO2max. J Strength Cond Res. 2012; 26: 548-554.
27. Morgan DW, Craib M. Physiological aspects of running economy. Med Sci Sports Exerc. 1992; 24: 456-461.
28. Saunders PU, Pyne DB, Telford RD, Hawley JA. Factors affecting running economy in trained distance runners. Sports Med. 2004; 34: 465-485.
29. George JD, Bradshaw DI, Hyde A, Vehrs PR, Hager RL, Yanowitz FG. A maximal graded exercise test to accurately predict VO2max in 18-65-year-old adults. Meas Phys Educ Exerc Sci. 2007; 11: 149-160.