Predictive accuracy of criteria used to assess maximal oxygen consumption

To evaluate criteria frequently used to designate an exercise test as maximal, 33 men and 18 women completed progressive incremental cycle ergometry to exhaustion with direct measurement of oxygen consumption (VO_2). On a separate day, subjects exercised at 115% of the maximal work rate attained in the first test following a 5-minute warm-up. If VO_2 exceeded that of the progressive test by ≥150 ml/min, subjects returned on a third day and pedalled at 125% of the first day's work rate$_{peak}$. This procedure was repeated until VO_2 increased <150 ml/min, and defined whether the progressive test was a maximal or nonmaximal test. There were 45 tests that met the criterion for maximum during the progressive test and six nonmaximal tests. Respiratory exchange ratio and 85% age-predicted maximal heart rate were sensitive criteria for a maximal test but were not specific. Attainment of age-predicted maximal heart rate and peak lactate >8 mmol/L were highly specific but insensitive measures of a maximal test. In the absence of a VO_2 plateau, age-predicted maximal heart rate and lactate >8 mmol/L can be used as indicators of maximal tests with a high degree of confidence. When age-predicted maximal heart rate or lactate >8 mmol/L are not attained, the test may still be maximal because negative predictive value is low. (Am Heart J 1992;123:922.)

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Maximal oxygen consumption (VO_{2max}) is the most widely used index of aerobic fitness[1-4] and is used to measure responses to training.[5] The gold standard for assessment of VO_{2max} is attainment of an oxygen consumption plateau (VO_2P). The attainment of VO_2P during increasing work suggests that maximal cardiac output and maximal oxygen extraction have been attained and that a healthy individual has reached the limits of his or her circulatory and respiratory capacity. However, the frequency that VO_2P is attained depends on how VO_2P is defined, the exercise protocol and the modality used, and the population tested.[1, 6-12] Different investigators* have reported the incidence of VO_2P in 17% to 98% of exercise tests.

In the absence of a clearly defined VO_2P, other criteria have been used to determine if a test is maximal. These criteria include the attainment of a Respiratory Exchange Ratio ≥1.10 (RER 1.10),[11, 13] Respiratory Exchange Ratio ≥1.15 (RER 1.15),[11, 14] 5-minute postexercise venous lactate ≥8.0 mmol/L,[11] and attainment of age-predicted maximum heart rate (APMHR).[15, 16] Although these criteria are frequently used in the literature to evaluate a maximal effort, they have not been studied as to how they specifically relate to attainment of VO_2P. The purpose of the present study was to examine the predictive accuracy of RER 1.10, RER 1.15, postexercise lactate, and APMHR with respect to the attainment of maximal exercise as defined by reaching an oxygen consumption plateau. Since attainment of 85% age-predicted maximal heart rate is used as an end point in some diagnostic stress tests, the predictive accuracy of this criterion was also evaluated.

METHODS

Subjects. Eighteen women and 33 men participated in this investigation (Table I). Subjects had no known cardiac or pulmonary disease. Each subject was informed as to the experimental procedures, completed a medical history, and signed informed consent statements in accordance with the guidelines of the Human Investigation Committee at Lenox Hill Hospital.

Experimental design. All testing was performed within a 2-week period on separate days. On day 1, subjects performed an incremental test to exhaustion on a Fitron cycle

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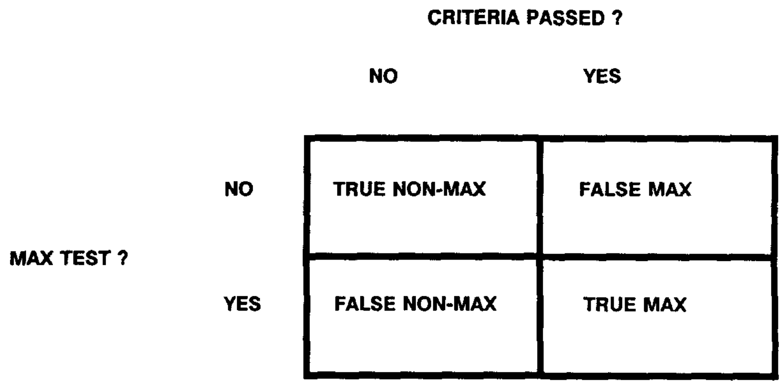

Fig. 1. Assessment of surpassing or not surpassing the criteria. *Max*, Maximal.

ergometer (Lumex Corp., Ronkonkoma, N.Y.). Work was increased 100 or 150 kilopond-meters (kpm) every minute depending on body size. Oxygen consumption was continuously measured with 20-second averaging by a SensorMedics 2900 or MMC Horizon measurement cart (SensorMedics Corp., Yorba Linda, Calif.). All tests for each subject were done with the same machine. Heart rate was monitored continuously with three leads by a Sensormedics Horizon electrocardiograph (ECG) (SensorMedics Corp.). The subjects continued cycling until they could no longer maintain their work rate. The investigators were aware of VO_2 and heart rate (HR) during the test; however, the subjects were encouraged to continue regardless of the values. Five minutes after the test, 37 of the subjects had forearm blood drawn nonischemically with a tuberculin syringe for blood lactate determination. Lactate was assayed with a YSI model 23L lactate analyzer (YSI Inc., Yellow Springs, Ohio) within 5 minutes of venipuncture.

On day 2, subjects warmed up for 2 minutes at 30% and then for 3 minutes at 50% of the peak work rate from day 1. Warm-up intensity was increased if heart rate did not reach 130 beats/min. Warm-up was followed by exercise at 115% of peak work rate from day 1 for at least 80 seconds.[10] If VO_{2peak} on day 2 did not exceed that of day 1 by >150 ml/min, the test on day 1 was considered to be maximal. If peak VO_2 on day 2 exceeded peak VO_2 from day 1 by ≥150 ml, the test on day 1 was not considered maximal and the subject returned for a third test. The third test included a 5-minute warm-up as on day 2, after which the subject exercised at 125% of peak work rate from day 1. If the subject continued to increase VO_{2peak} by >150 ml/min, the tests were repeated, increasing exercise work rate by 10% until the increase in VO_{2peak} from the previous test did not exceed 150 ml/min. Increases in VO_{2peak} by 150 ml/min were chosen a priori based on The American College of Sports Medicine's calculation that an increase in 100 kpm should elicit an increase of 200 ml/min, and all increments during the initial test were at least 100 kpm/min and none were greater than 150 kpm/min.[15]

Statistical analysis. Surpassing of the following criteria during the first test was assessed as being either positive or negative (Fig. 1): RER ≥1.10 (RER1.10); RER ≥1.15 (RER 1.15); lactate ≥8.0 mmol/L (LAC8); HR ≥ age-predicted maximal heart rate (APMHR), defined as 220-age[15]; and 85% APMHR ≥85% age-predicted maximal heart rate (85 APMHR).

Table I. Subject characteristics (mean ± SD)

Variable	*Mean (SD)*	*Range*
Age (yr)	30.6 (6.1)	18-45
Weight (kg)	68.6 (10.6)	43.8-86.6
Body fat %	14.5 (3.1)	9.5-25.7
VO_{2max} (L/min)	3.35 (.92)	1.54-5.29
VO_{2max} (ml/kg/min)	49.2 (9.6)	28.8-70.8
Work $rate_{max}$ (kpm)	1480.6 (446.8)	800-2400
Heart $rate_{max}$ (beats/min)	182.1 (9.1)	160-202
RER_{max}	1.22 (.1)	1.10-1.54
$Lactate_{peak}$ (mmol/L)	8.12 (1.5)	4.4-11.1

Sensitivity, the percentage of maximal tests (<150 ml/min increase) that exhibit a maximal test response (by the criteria); specificity, the percentage of a nonmaximal tests (>150 ml/min) that do not exhibit a maximal test (by the criteria); positive predictive value (PPV) (the probability of a test being maximal if a criterion was attained); and negative predictive value (NPV) (probability of a test not being maximal if the criterion was not exceeded) were calculated for each criterion (Fig. 2).

RESULTS

VO_{2peak} was defined as the highest VO_2 attained on day 1 and VO_{2max} was the maximal oxygen consumption attained on the test that met the leveling-off criteria. Eighty-eight percent of the subjects attained VO_{2max} on the day 1 test. The mean VO_{2peak} on day 1 (3.28 L/min) differed significantly ($p < 0.05$) from the mean VO_{2max} (3.35 L/min), although the difference was less than 150 ml/min. Six subjects (12%) surpassed the first test VO_{2peak} on subsequent tests by ≥150 ml/min.

The sensitivity of RER 1.10, RER 1.15, and 85

$$\text{Sensitivity} = \frac{\text{True Max}}{\text{True Max + False Non-Max}}$$

$$\text{Specificity} = \frac{\text{True Non-Max}}{\text{True Non-Max + False Max}}$$

$$\text{Positive Predictive Value} = \frac{\text{True Max}}{\text{True Max + False Max}}$$

$$\text{Negative Predictive Value} = \frac{\text{True Non-Max}}{\text{True Non-Max + False Non-Max}}$$

Fig. 2. Formulas for sensitivity, specificity, and positive and negative predictive values. *Max*, Maximal.

Table II. Sensitivity, specificity, positive (PPV) and negative (NPV) predictive values of the criteria

	Sensitivity (%)	*Specificity (%)*	*PPV (%)*	*NPV (%)*
RER 1.10	100	0	88	0
RER 1.15	82	17	82	11
APMHR	25	83	92	13
85 APHMR	98	0	88	0
LAC8	44	100	100	5
APMHR + RER 1.15	25	83	92	13
APMHR + RER 1.15	22	83	91	13
LAC8, APMHR + RER1.15	9	100	100	5
LAC8 + RER 1.15	36	100	100	4
LAC8 + APMHR	9	100	100	3
RER 1.15 + 85APMHR	85	17	17	11
LAC8 + 85 APMHR	28	100	100	5
RER1.15, LAC8 + 85 APMHR	36	0	93	0

APMHR were in excess of 80%; the specificity of each of these criteria were all below 20%. In contrast, APMHR had low sensitivity (25%) and high specificity (83%). LAC8 had a sensitivity of 44% and a specificity of 100% (Table II). The addition of APMHR or 85 APMHR to LAC8, RER 1.10 or RER 1.15 reduced the sensitivity of each parameter used independently. LAC8 added to RER 1.15 improved specificity (Table II). The positive predictive value of each parameter examined was greater than 80%, while the negative predictive values were below 20% (Table II).

DISCUSSION

Most of the subjects who attained VO_{2max} during the day 1 test attained or exceeded RER 1.10, RER 1.15, and 85 APMHR, but these criteria were also likely to be attained during a nonmaximal test. Peak RER 1.10, RER 1.15, and 85 APMHR are therefore not stringent enough to distinguish a maximal from a nonmaximal test.

In contrast, the high specificity of achieving APMHR makes it a very stringent criteria for VO_{2max}, but the low sensitivity indicates that many subjects who reached max on day 1 did not attain APMHR. The higher sensitivity of LAC8 (44%) combined with its 100% specificity, make LAC8 a better overall test than APMHR.

In the present investigation, we defined VO_{2max} as when a work rate increase of 15% (average of 227 kpm increase) resulted in a VO_2 difference of less than 150 ml/min. This definition was derived empirically by Taylor et al.,[12] and as such is not a gold standard. In addition, the 200 ml/min per 100 kpm work increase suggested by the American College of Sports Medicine is a predicted response and can vary between individuals. Because of the lack of a gold standard, any test of sensitivity or specificity for VO_{2max} testing is inherently flawed. Nevertheless, the >150 ml/min criterion cited in the literature as standard[2,13] was used here. The present study demonstrates how commonly used indices of attainment of VO_{2max} relate to the >150 ml/min criteria of Taylor et al.[12]

Although our criteria for VO_2P were more stringent than some of those used in previous studies,* 88% of our subjects attained VO_{2max} during the first test, and only five subjects required more than two tests to demonstrate a plateau. This is consistent with the findings of previous studies in which from 17% to 98% of the subjects attained VO_2 plateau† during either continuous or discontinuous exercise. The wide variation in the percentage of subjects attaining VO_2 plateau in previous studies is the result of differences in protocol and modality,‡ definition of VO_2 plateau,[2,6,7] and training status of the subjects.[6,12]

Previous studies that have examined the relationship of maximal criteria to attainment of VO_2 plateau are conflicting. Trained children, for example, 35% of whom achieved VO_2P, had low maximal RER (1.0) and lactate levels (6.5 mmol/L).[6] In men with average VO_{2max} of 30.3 ml/kg/min between ages 40 and 65,[17] 43% achieved VO_2 plateau and fewer than 50% achieved $RER_{peak} \geq 1.15$. However, despite the low percentage that attained VO_2 plateau, 78% attained $lactate_{peak} \geq 8.0$ mmol/L and 76% attained APMHR. In another study of men and women, fewer than 40% attained VO_2 plateau, but 97% attained APMHR and 76% achieved $RER_{peak} \geq 1.10$.[13] Niemela et al.[2] found that in men and women with VO_{2max} between 27.2 and 35.7 ml/kg/min, 18% demonstrated VO_2P while 66% attained APMHR and 9% had $RER_{peak} \geq 1.15$.

The positive predictive value of all criteria tested was greater than 80%, and the negative predictive value of all criteria tested was less than 15%. However, the positive and negative predictive values of the criteria tested are influenced by the small number of nonmaximal day 1 tests, and only apply to the specific population tested. Most of our subjects were in good physical condition (VO_{2max} = 49.2 ml/kg/min). Several subjects were competitive cyclists, and almost all were familiar with maximal exercise testing. The high motivation that is typical of this population may have contributed to the high proportion of subjects attaining VO_{2max} on the first test. In studies of well-trained subjects, from 50% to 93% attained VO_{2max},[2,12] while untrained subjects in the same study achieved VO_{2max} only 17% of the time.[2] Untrained subjects may stop the test because of pain at higher work rates rather than because of a maximal cardiorespiratory effort.

The present results suggest that when testing healthy, motivated subjects the criteria tested in this study can be used as indicators of maximal tests with a high degree of confidence. The caveat is that when these criteria are not attained because the negative predictive value is low, the test may still be maximal. Further work is needed to assess the predictive accuracy of these criteria in other populations, including untrained normal individuals and patients with cardiac disease.

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†References 1, 2, 6, 8, 9, 14, and 17.

‡References 2, 6, 8, 9, 12, and 14.

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