Individualized Ramp Treadmill*  
Observations on a New Protocol  
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The many different approaches to exercise testing have hindered the consistent interpretation of hemodynamic, electrocardiographic, and ventilatory gas exchange responses. One of the most influential approaches is the choice of the exercise protocol. Recent data suggest that the protocol can have an important impact on test sensitivity, the reason for test termination, the ST/HIR slope calculation, the interpretation of gas exchange responses, and the accuracy with which oxygen uptake is predicted from work rate. Recent recommendations for optimizing the test have focused on the test duration, reducing the increments in work rate, and individualizing the test relative to the purpose of the test and the subject tested. We describe a treadmill test which considers these recommendations for optimizing exercise testing.

The quest for an "optimal" test for assessing electrocardiographic and/or gas exchange responses to exercise spans 7 decades. Several protocols have evolved that have become common, and while the treadmill is the most frequently used mode in the United States, the cycle ergometer remains popular in Europe. Advantages and disadvantages of various exercise modes and protocols have been discussed at length. An ideal protocol should consider the following: (1) the purpose of the test; and (2) the subject tested. For most exercise tests, however, the choice of protocol is dictated by tradition, equipment, or convenience. For example, of the treadmill protocols, more than half the laboratories in North America employ the standard Bruce test, even though its large increments in work make it inappropriate for many patients with cardiovascular diseases.

A number of investigators have suggested individualizing tests rather than employing a standardized protocol for every patient. Redwood et al demonstrated that such tests were superior for the evaluation of pharmacologic treatment effects; protocols placing heavy or abrupt demands on patients with angina appeared to mask the salutary effect of nitroglycerin. Buchfuhrer and associates reported that the highest values for maximal oxygen uptake were observed in tests individualized to last approximately 10 min. A test that facilitates this approach is the ramp test, in which gradual changes in work can be individualized considering the patient's age, fitness, disease status, and the purpose of the test. Recently our laboratory compared individualized ramp treadmill and cycle ergometer tests with commonly used standard protocols. We noted that the slope of the relationship between changes in work rate and changes in measured oxygen uptake were highest when using the ramp tests compared with commonly used incremental protocols. These findings have a number of clinical implications regarding predicting oxygen uptake, exercise prescription, and improving the test in general. The following is a descriptive report that expands these prior results by reviewing our experience with 200 apparently healthy individuals using an individualized ramp treadmill protocol.

**METHODS**

**Subjects**

One hundred seventy-three male and 27 female subjects (mean age, 45 ± 13 years) participated in the study. They were selected to fit into hypertensive (mean diastolic blood pressure >85 mm Hg on 24-h ambulatory monitoring, n = 47) or normotensive (mean diastolic blood pressure <85 mm Hg on 24-h ambulatory monitoring, n = 153) groups. All subjects were otherwise healthy and had no history of cardiovascular disease. None were taking medications at the time of the study. Subject characteristics are presented in Table 1. All rights and privileges were honored in accordance with an established human subjects protocol, and informed consent was obtained.

**Exercise Testing**

Each subject performed 8 exercise tests. They were requested to abstain from food, coffee, and cigarettes for at least 3 h prior to testing. The first test was performed to familiarize subjects with the testing procedure and gas exchange apparatus, and to determine maximal oxygen uptake. This test consisted of a modified Balke Ware protocol with the speed individualized from 2.5 to 4.5 mph depending on the subject's height and fitness. Tests were continued to volitional fatigue/dyspnea, and the Borg 6 to 20 scale was used to quantify subjective level of exertion each minute.

The second test, performed approximately 1 week later, was designed as follows. All subjects walked for 1 min at a workload of 2.0 mph/0% grade. Based on the initial test, an individualized peak treadmill speed was chosen for each subject. The ramp rate (rate of continuous change in speed and grade) was calculated using the following: (1) the baseline maximal oxygen uptake; (2) the predetermined peak treadmill walking speed; and (3) a projected test duration of 10 min for each subject. A computer program was written in Basic language to facilitate these calculations for each subject. The oxygen cost of the treadmill speed and grade was calculated using equations commonly applied for predicting oxygen uptake from treadmill and cycle ergometer work.

An example of

<table>
<thead>
<tr>
<th>Table 1—Subject Characteristics (Mean ± SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Male</td>
</tr>
<tr>
<td>n = 173</td>
</tr>
<tr>
<td>Female</td>
</tr>
<tr>
<td>n = 27</td>
</tr>
<tr>
<td>Age, yr</td>
</tr>
<tr>
<td>45 ± 13</td>
</tr>
<tr>
<td>Weight, kg</td>
</tr>
<tr>
<td>84 ± 13.5</td>
</tr>
</tbody>
</table>

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* Indicates that the article is an invited commentary and is not subject to the usual peer review process.
the ramp test is illustrated in Figure 1. With the exception of the protocol, all exercise data, including hemodynamic, gas exchange, and perceived exertion were collected as on the initial test. The 10-min duration was used only as an estimated goal, so that the maximal external work rate on the second test would correspond to the measured maximal oxygen uptake obtained on the baseline test; however, exercise was continued to volitional fatigue.

Respiratory Gas Exchange

Respiratory gas exchange variables were determined continuously throughout the exercise test (using the Medical Graphics Corporation 2001 System). Gas exchange variables analyzed were as follows: oxygen uptake (\( \text{VO}_2 \), ml/kg/min, STPD); carbon dioxide production (\( \text{VCO}_2 \), L/min, STPD); minute ventilation (\( \text{VE} \), L/min, BTPS); oxygen pulse (\( \text{VO}_2 \), ml/min divided by heart rate); and respiratory exchange ratio (RER, \( \text{VCO}_2 \) divided by \( \text{VO}_2 \)). One-minute ventilatory samples were used throughout exercise. However, when measured and predicted maximal oxygen uptake were compared, an eight-breath moving average sample11 corresponding to the treadmill speed and grade at peak exercise was used.

Statistics

Data were entered into a spreadsheet (Quattro Pro) from which means and standard deviations were performed. A program (Statistical Graphics Corporation, Bethesda, Md) was used to compare regression lines between oxygen uptake and work rate. Student’s t-tests for paired observations were used to evaluate differences between measured and predicted maximal oxygen uptake.

RESULTS

All subjects completed the 2 exercise tests without complication. Hemodynamic and gas exchange variables at rest and maximal exercise for all subjects are presented in Table 2. Characteristics of the ramp test are presented in Table 3. Table 4 contrasts the regression equations and correlations between measured oxygen uptake and treadmill time in the present and previous studies. The relationship between measured and predicted oxygen uptake throughout exercise is illustrated in Figure 2. The relationship between measured and predicted maximal oxygen uptake is illustrated in Figure 3. Figure 4 compares maximal MET values predicted from a specific activity questionnaire vs those achieved on the treadmill.

Reasons for Stopping Exercise

General fatigue and/or leg fatigue was reported as the major reason for stopping on 145 (72%) of tests performed. Twenty-nine subjects (14%) stopped due to shortness of breath, 16 (8%) stopped due to leg (ankle, knee, foot) pain,

### Table 2—Hemodynamic and Gas Exchange Data at Rest and Maximal Exercise

<table>
<thead>
<tr>
<th>Data</th>
<th>Mean ± SD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Heart rate, beats/min</td>
<td>66 ± 11</td>
</tr>
<tr>
<td>Systolic blood pressure, mm Hg</td>
<td>136 ± 20</td>
</tr>
<tr>
<td>Diastolic blood pressure, mm Hg</td>
<td>88 ± 16</td>
</tr>
</tbody>
</table>

### Table 3—Characteristics of the Ramp Test

<table>
<thead>
<tr>
<th></th>
<th>Mean ± SD</th>
<th>Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp rate, % grade/min</td>
<td>2.32 ± 0.82</td>
<td>0.5-4.1</td>
</tr>
<tr>
<td>Rate of change in speed, mph/min</td>
<td>1.18 ± 0.45</td>
<td>0.4-2.4</td>
</tr>
<tr>
<td>Peak speed, mph</td>
<td>3.3 ± 0.4</td>
<td>2.5-4.5</td>
</tr>
<tr>
<td>Peak grade, %</td>
<td>16.0 ± 5.6</td>
<td>3.5-25</td>
</tr>
<tr>
<td>Peak treadmill time, min</td>
<td>9.47 ± 1.8</td>
<td>5.4-14.7</td>
</tr>
<tr>
<td>Peak predicted maximal oxygen uptake, ml/kg/min</td>
<td>37.7 ± 10.7</td>
<td>18.4-60.3</td>
</tr>
</tbody>
</table>

### Table 4—Comparison of the Ramp Treadmill to Previous Studies Relating Treadmill Time or Workload to Measured Oxygen Uptake in Normal Subjects

<table>
<thead>
<tr>
<th>Author</th>
<th>Protocol</th>
<th>Regression Equation</th>
<th>Mean Maximal Uptake ± SD, ml/kg/min</th>
<th>r</th>
<th>Standard Error of the Estimate</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bruce et al</td>
<td>Bruce</td>
<td>( Y = 3.29X + 4.07 )</td>
<td>37.3 ± 8.2</td>
<td>0.93</td>
<td>34.9</td>
</tr>
<tr>
<td>Pollock et al</td>
<td>Bruce</td>
<td>( Y = 4.33X - 4.66 )</td>
<td>40.0 ± 7.2</td>
<td>0.88</td>
<td>0.096</td>
</tr>
<tr>
<td>Moniz et al</td>
<td>Balke</td>
<td>( Y = 1.44X + 14.99 )</td>
<td>39.4 ± 5.9</td>
<td>0.92</td>
<td>0.25</td>
</tr>
<tr>
<td>Roberts et al</td>
<td>Modified</td>
<td>( Y = 3.91X - 8.88 )</td>
<td>36.8 ± 6.6</td>
<td>0.93</td>
<td>2.56</td>
</tr>
<tr>
<td>Froelicher et al</td>
<td>Bruce</td>
<td>( Y = 3.18X - 0.59 )</td>
<td>44.5 ± 5.8</td>
<td>0.82</td>
<td>3.34</td>
</tr>
<tr>
<td>Martin et al</td>
<td>Balke</td>
<td>( Y = 1.25X + 9.42 )</td>
<td>41.6 ± 5.0</td>
<td>0.86</td>
<td>2.65</td>
</tr>
<tr>
<td>Myers et al (present study)</td>
<td>Ramp</td>
<td>( Y = .72X + .37 )</td>
<td>33.1 ± 10.7</td>
<td>0.87</td>
<td>4.35</td>
</tr>
</tbody>
</table>
Individualized Ramp Treadmill (Myers et al)

**Figure 2.** The relationship between measured and predicted oxygen uptake each minute throughout exercise. The correlation coefficient between the two variables was 0.93 (SEE = 3.96 ml/kg/min, p < 0.001). The regression equation was $Y = 0.79X + 3.02$.

4 (2%) stopped due to back pain, 4 (2%) stopped due to dizziness, 1 stopped due to nausea, and 1 was stopped due to a hypertensive response. The latter subject was included in the analysis as he achieved a maximal perceived exertion of 19.

**Maximal Exercise**

The mean maximal perceived exertion was 18.9 ± 1.3 and the maximal respiratory exchange ratio was 1.16 ± 0.14 (Table 2). These values suggest that maximal exercise was generally achieved for the group. The mean maximal heart rate attained was 168 ± 17 which is roughly equal to that expected for age. Maximal oxygen uptake was 33.1 ± 10.7; male subjects achieved approximately 100% of that expected for sex and age, while female subjects achieved approximately 93% of that expected for sex and age.

**Relation Between Oxygen Uptake and Work Rate**

Figure 2 illustrates the relationship between minute by minute changes in measured oxygen uptake and those predicted by the work rate. The slope of the relationship for all subjects was 0.78 (SEE = 0.008 ml/kg/min, p < 0.001).

**Figure 3.** The relationship between measured and predicted maximal oxygen uptake. The correlation coefficient between the two was 0.87 (SEE = 4.35 ml/kg/min, p < 0.001). The regression equation was $Y = 0.72X + 3.67$.

and the correlation was 0.93 (SEE = 4.0, p < 0.001). The regression equation was $Y = 0.79X + 3.02$. The slope of the relationship did not differ between values observed below 5 min of exercise (slope = 0.78, SEE = 0.015, r = 0.85, SEE = 3.23, p < 0.001), and those above 5 min of exercise (slope = 0.73, SEE = 0.014, r = 0.76, SEE = 4.66, p < 0.001).

**Predicted vs Measured Maximal Oxygen Uptake**

Figure 3 illustrates the relationship between maximal ventilatory oxygen uptake and oxygen uptake predicted from peak treadmill speed and grade. The correlation coefficient between the two variables was 0.87 (SEE = 4.35 mg/kg/min, p < 0.001). The regression equation was $Y = 0.72X + 3.67$.

**Maximal METs Calculated from Treadmill Work vs Estimated from Questionnaire**

Figure 4 illustrates the relationship between exercise capacity, expressed in METs, estimated from a specific activity questionnaire (Y axis) and that calculated from treadmill speed and grade at peak exercise (X axis).

The individualized approach offers several advantages for cardiopulmonary exercise testing. First, most protocols employ fixed work increments between stages. These increments are large for some patients and small for others. Relatively large increments for some patients can cause a discrepancy between oxygen uptake and treadmill work rate, which can lead to premature termination of exercise and limit the evaluation of cardiopulmonary function. Panza and coworkers, for example, recently observed that the correlation between ischemic responses on treadmill testing vs those on 48-h ambulatory monitoring was markedly improved when using a gradual protocol (<1 MET increments) compared with a protocol using large increments (Bruce protocol, 2 to 3 MET increments). Second, uneven increments in work limit the application of some gas exchange parameters, such as the $\dot{V}O_2/\dot{W}$ relationship and
the ventilatory threshold. Third, several recent studies have suggested that a test duration of 8 to 12 min is “optimal” for assessing cardiopulmonary function.\(^7,8,11,13\) This duration has been justified on the basis of better reliability for studying the effects of therapy,\(^8,13\) higher values for maximal oxygen uptake,\(^8\) and an improvement in the relationship between oxygen uptake and work rate compared with shorter protocols employing large work increments.\(^8\) Because a major feature of the ramp test is an individualized change in work rate, a desired test duration can be roughly achieved.

Although we have recently compared the ramp test with standard treadmill and cycle ergometer protocols in a small group of patients with heart disease,\(^9\) to our knowledge, the present report is the first thorough evaluation of the protocol in a large sample. As part of a larger trial of normotensive and hypertensive subjects, this sample provided a convenient opportunity to evaluate the ramp treadmill test. Although 24% of these subjects had hypertension and thus high blood pressures were present at rest and during exercise, they were otherwise healthy, and oxygen kinetics should not have been affected. The mean treadmill time of 9.5 ± 1.8 min indicates that the targeted duration was generally achieved, despite a wide spectrum of age and fitness levels.

Ramp testing using a cycle ergometer has been employed by several laboratories over the last decade for research purposes.\(^4,11,16,18\) Whipp and associates\(^11\) first described the ramp function test as a valid and reproducible means of assessing cardiopulmonary function. Davis et al\(^16\) extended these findings by demonstrating that the basic parameters of aerobic function studied by Whipp and coworkers\(^11\) (maximal oxygen uptake, the ventilatory threshold, the time constant for \(\dot{V}O_2\) kinetics, and work efficiency) were valid over a wide range of ramp rates (20 to 50 W/min) on a cycle ergometer. At higher ramp rates, however (100 W/min), oxygen kinetics and work efficiency could not be estimated. This finding underscores the value of choosing an individualized ramp rate for each subject. Ramp cycle ergometry, because of the constant increases in work, has intuitive advantages for assessing blood lactate and acid-base relationships during exercise,\(^11,16\) pharmacologic intervention,\(^16,18\) and the oxygen uptake/work rate relation and other measures of oxygen kinetics.\(^11,16,21,24,25\)

Work is quantified with less precision on the treadmill compared with a cycle ergometer, as it is more dependent on walking efficiency, handrail holding, and habituation. Thus, a greater degree of error would appear to be present when predicting work on the treadmill for exercise prescription or other purposes. Our previous work using ramp testing on both the treadmill and cycle ergometer suggests that the contrast in oxygen kinetics between normal subjects and patients with heart disease is present with either mode, despite the less precise quantification of work on the treadmill. At present, there are few treadmill controllers available for programming ramp tests. Although the ramp treadmill lacks widespread application and must be validated by other laboratories, the advantages of the treadmill (higher maximal oxygen uptake, more subjects are accustomed to walking, its widespread use in the United States) and the advantages of the ramp discussed above would appear to make it well-suited for many clinical applications.

**Predicted vs Measured \(\dot{V}O_2\) Throughout Exercise**

The slope of the relationship between measured and predicted oxygen uptake (Figure 2) is an expression of the degree of change in one variable for a given change in another. The ramp test lends itself well to an evaluation of slope since the change in the variable expressed on the X axis (the work rate) is constant. Thus, the slope illustrates how well ventilatory oxygen uptake (Y axis) increased in accordance with the demands of the work (X axis) throughout the test. We have previously reported that the slope of this relationship is reduced using protocols with large increments in work (for example, slopes of roughly 0.60 were observed on the Bruce treadmill and 50 W/stage cycle ergometer vs roughly 0.80 on ramp treadmill and cycle ergometer tests) in a combined group of patients and normal subjects.\(^8\) The slope of 0.78 and the correlation of 0.93 observed in the present study confirm our previous results. It is noteworthy that the standard error of the \(Y\) estimate (3.96 ml/kg/min) suggests that any given submaximal exercise level can be predicted within approximately ± 2 METs with 95% confidence. It should be noted further that the present group was free of cardiovascular disease, and since patients with disease are known to have reduced oxygen kinetics, this accounts in part for the high slope. Nevertheless, the association between measured and predicted oxygen uptake throughout exercise in the present and previous studies\(^8,11\) suggests that the ramp test has advantages other protocols when the need for predicting oxygen uptake exists.

Previous studies have noted a disruption of the relation between oxygen uptake and work rate at higher levels of exercise.\(^11,13,19,27,28\) Roston et al\(^20\) for example, demonstrated that oxygen kinetics were attenuated at work rates above the lactate threshold, and the magnitude of the slower rise in oxygen uptake was highly correlated with the increase in lactate. Mechanisms that have been suggested to account for the altered oxygen uptake/work rate relation at high levels of exercise include reduced efficiency of oxygen uptake due to anaerobic metabolism, added oxygen cost of gluconeogenesis in the liver from lactate,\(^24\) muscle temperature,\(^24\) and the metabolic effects of catecholamines.\(^25\) In the present study, however, the slope of the oxygen uptake/work rate relation did not differ at high (>5 min: slope = 0.73, SEE = 0.014) or low (<5 min: slope = 0.78, SEE = 0.015) work intensities. This is in agreement with the observations of Whipp et al\(^16\) who reported a first-order linear relation between oxygen uptake and work rate both above and below the ventilatory threshold among normal subjects using a ramp cycle ergometer. Possible explanations for these differences include the effects of disease,\(^8,11,13,18\) differences in the exercise protocol,\(^8,11,20\) and differences in methods of defining oxygen kinetics and the oxygen uptake/work rate relation.

**Maximal Ventilatory vs Maximal Predicted Oxygen Uptake**

Because of its many clinical applications, the most important concern is the influence of these factors on maximal exercise capacity. Despite the many reports concerning the shortcomings of estimating maximal oxygen uptake,\(^11,13,18,29,30\) the direct measurement of oxygen uptake using gas exchange techniques remains somewhat limited due to the added cost, time, and personnel required. As mentioned, the
precision with which maximal oxygen uptake is predicted is known to be affected by both the protocol and the presence of disease. 8,11,13,18,20 One major criticism of the predicted method is that protocols which employ large increments in work result in a less accurate estimation of oxygen uptake. 4 The constant, continuous work increases in the ramp protocol would appear to be 1 method of overcoming these limitations.

The correlation between measured and predicted maximal oxygen uptake using the ramp treadmill (r = 0.87) falls in the range of 0.82 to 0.93 observed in previous studies using various incremental protocols among normal subjects (Table 4).10,25-27 Two points should be considered, however, in comparing the ramp and incremental protocols in this context. First, previous studies have compared measured oxygen uptake with treadmill time, which can differ markedly from predicted oxygen uptake. Second, the influence of incomplete stages makes the prediction of oxygen uptake from treadmill time or workload somewhat tenuous when using incremental protocols. In the present study, subjects were “credited” with both the predicted and measured oxygen uptake value at the instant the test was terminated. While this alleviates the problem of an incomplete stage, naturally maximal oxygen uptake would still be overestimated.

Individualizing the Ramp Rate: The Specific Activity Questionnaire

One obvious shortcoming of the approach described herein was the use of 2 tests. We performed the first test for 2 purposes: (1) to habituate subjects to the treadmill and gas exchange apparatus; and (2) to determine maximal oxygen uptake. Our goal was to evaluate how accurately a targeted test duration could be attained using the individualized approach; a measure of each subject’s exercise capacity was necessary to do this with precision. Naturally, such precision would not generally be necessary. An estimation of a given patient’s exercise tolerance would generally be adequate to appropriately individualize the ramp rate.

We have recently employed a modified specific activity questionnaire28 to estimate exercise capacity prior to testing for this purpose. This consists of a short, self-administered progressive series of questions pertaining to activities of daily living. Some example questions are presented in Table 5. Figure 4 illustrates the relationship between MET values achieved on the treadmill and those estimated from the questionnaire. Although the mean MET values did not differ between those achieved on the treadmill and those estimated by the questionnaire (8.4 ± 3.5 vs 8.8 ± 2.6, respectively), a significant degree of variation was present. Moreover, while patients with low MET levels tended to overestimate their exercise capacity, patients who achieved high MET levels tended to underestimate their exercise capacity. Nevertheless, the significant correlation (r = 0.69, p < 0.001) and 95% confidence limits suggest that a reasonable estimate of a patient’s exercise capacity can be obtained quickly for the purposes of individualizing the ramp rate.

CONCLUSIONS

In recent years, a call for “optimizing” exercise testing, including customizing the test given the specific conditions, patient, or test purpose has been made.8,11,13,18 The ramp test has several features that allow it to meet these recommendations. Herein we have described a method of performing the test. Naturally, the approach was empirical and relied greatly on intuition. The protocol must be validated in different patient populations. Moreover, to our knowledge, this test has never been used to evaluate a clinical intervention. More data are necessary to confirm its usefulness in clinical trials.

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