Maximal Oxygen Consumption

A test of aerobic fitness that truly qualifies as a laboratory test is the Maximal Oxygen Consumption (VO$_2$max) Test. Although this test may involve a substantial anaerobic contribution to metabolism at the terminal portion of the test, it is primarily an aerobic test.

Whereas the run/jog/walk and cycle tests attempt to predict aerobic power as accurately as possible, the VO$_2$max Test measures aerobic power. The run/jog/walk tests, for example, predict maximal oxygen consumption based on the relationship between maximal oxygen consumption and time or distance of running or walking; some run/jog/walk tests combine running or walking performance with heart rate. The step tests and cycle tests estimate the maximal oxygen consumption based on the relationship among heart rate, oxygen consumption, and power level. Because the VO$_2$max Test directly measures oxygen consumption, it requires more expensive and sophisticated equipment than that required by field tests.

In this chapter, the direct measurement of oxygen consumption is described for submaximal and maximal exercise. Special importance is given to the latter stages of the exercise protocol, because that is when the maximal oxygen consumption typically occurs.

Purpose of the Maximal Oxygen Consumption Test

The purpose of the Maximal Oxygen Consumption Test is to measure aerobic fitness. Aerobic fitness is synonymous with several other terms, such as aerobic power, cardiovascular fitness, cardiovascular endurance, circulorespiratory endurance, and cardiorespiratory endurance. Cardiovascular fitness, as estimated by VO$_2$max, is inversely related to coronary heart disease and all-cause mortality.

The Maximal Oxygen Consumption Test has received more recognition than any other exercise physiology laboratory test. Testimony to this is the fact that the purpose of many field tests is to predict maximal oxygen consumption—the variable that often has been used synonymously with aerobic fitness. Traditionally, no other single laboratory test has been used as frequently to indicate a person's aptitude for success in events calling upon maximal efforts longer than 2 min. In addition, combined with some anaerobic tests, it helps indicate success for events lasting 1–3 min. In conjunction with measures of efficiency (economy), ventilatory threshold/breakpoint, glycogen storage, acclimatization, and fractional utilization of maximal oxygen consumption, the VO$_2$max Test is also an important indicator of success for all-out events lasting between 20 min and 4 h.

Also, the Maximal Oxygen Consumption Test provides insight into the cardiorespiratory system. For example, the clinical severity of disease decreases with an increase in functional aerobic fitness. Thus, the Maximal Oxygen Consumption Test has been used to assess not only aerobic fitness, but also the abilities of the cardiovascular and respiratory systems to transport and diffuse oxygen.

Physiological Rationale

The ability to consume oxygen is important for the metabolic function of body cells. Cellular activity is dependent upon oxygen because the cell derives its energy from adenosine triphosphate (ATP). Aerobic metabolism produces large volumes of ATP via the oxidative pathway. This pathway reflects the ability of the muscles’ mitochondria to synthesize the phosphagen ATP.

The maximal consumption of oxygen depends not only upon the cells’ ability to extract and use oxygen but also upon the ability of the cardiovascular and respiratory systems to transport this oxygen to the cells. Cardiovascularly, the transport of oxygen is represented by the cardiac output, the amount of blood pumped by a heart ventricle per minute. Thus, a greater maximal cardiac output leads to a greater maximal oxygen consumption under normal conditions. The respiratory system’s transport of oxygen is represented by ventilation, which is measured as liters of air per minute. A greater ventilation capacity is usually associated with a greater maximal oxygen consumption. It now appears that respiratory muscle work during heavy maximal exercise affects exercise performance by decreasing leg blood flow.

The term maximal oxygen consumption is usually used to denote the single highest oxygen consumption elicited during graded exercise to exhaustion. Because oxygen consumption depends on the amount of muscle mass involved, exercise test modes like the treadmill and cross-country ski ergometer that use more muscle mass yield higher values than a cycle ergometer or step test. Specifically, when VO$_2$ is measured in most people on the treadmill versus the cycle ergometer, the value is 5–10% higher on a treadmill. So, if one participant completes several
exercise tests using different modes, the test that yields the highest \( \text{VO}_2 \) value would be used as the true maximal oxygen consumption (\( \text{VO}_2\max \)). Another term often used is peak oxygen consumption, which is measured during a specific test, but it may not truly be the highest or maximal oxygen consumption possible. There are generally two different conditions where the term peak oxygen consumption (\( \text{VO}_2\text{peak} \)) is used. The first is as described above, where exercise tests using different modes elicit different oxygen consumption values. The highest recorded value (recorded on the treadmill, for example) would be considered the maximal oxygen consumption, whereas any lower values (recorded on a cycle ergometer or step test, for example) would be considered peak oxygen consumptions. The second condition is where symptoms or a lack of motivation limit the participant’s ability to reach a true physiological maximum. Participants may voluntarily stop during an exercise test due to leg pain, chest pain, dyspnea (a feeling of being unable to breathe enough air), or other symptoms prior to reaching a maximal effort. Or a participant simply may not be motivated sufficiently during the test, resulting in a less than maximal effort. Thus, maximal oxygen consumption is the term used for the highest possible value attained during a maximal-effort graded exercise test using a large muscle mass, and peak oxygen consumption can be used to describe any value attained during one particular test that may be lower than maximal oxygen consumption due to the mode of exercise, physical symptoms, or a lack of motivation. For simplicity, maximal oxygen consumption (\( \text{VO}_2\max \)) is used almost exclusively throughout this laboratory manual. It should be understood, however, that every graded exercise test does not necessarily yield a true maximal oxygen consumption, but it will always result in a peak oxygen consumption.

**METHODS**

The methods and procedures for the administration of oxygen consumption (metabolic) testing may seem complicated, especially for first-year exercise physiology students. However, it is certainly possible for novices to gain an appreciation and understanding of maximal oxygen consumption testing simply by observing the participant and by monitoring the instruments during the exercise test. The methods include a description of the equipment, the exercise protocol, the procedures, and the calculations. A description of the accuracy of the \( \text{VO}_2\max \) Test is in Box 15.1.

**Equipment**

Until the 1970s, the equipment used for measuring oxygen consumption consisted of several instruments purchased from separate manufacturers. The investigator then would interface the individual instruments so that online testing could be accomplished, or the investigator would collect the exhaled air in special bags for post-test analysis of oxygen and carbon dioxide concentrations and ventilation volumes. Today a variety of manufacturers combine the individual components into a single package. These interfaced consoles include a computer to make all the calculations for deriving the metabolic and respiratory values (Ametec™; Consentius Technologies). Improved and consolidated instrumentation has led to portable and breath-by-breath capabilities in measuring oxygen consumption (Cosmed™; Sensor Medics).

**Ergometers**

It is best to use the type of ergometer that simulates the type of movement for which the participant has been training. For example, runners should be tested on treadmills, cyclists on cycle ergometers, rowers on rowing ergometers.
Table 15.1  Conversion Between Units for Treadmill Speed and Grade

<table>
<thead>
<tr>
<th>Speed (Based on 1 mph = 1.609 km-h⁻¹ = 29.8 m-min⁻¹)</th>
<th>mph</th>
<th>km-h⁻¹</th>
<th>m-min⁻¹</th>
<th>mph</th>
<th>km-h⁻¹</th>
<th>m-min⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.7</td>
<td>2.7</td>
<td>46</td>
<td>5.5</td>
<td>8.8</td>
<td>147</td>
<td></td>
</tr>
<tr>
<td>2.0</td>
<td>3.2</td>
<td>54</td>
<td>6.0</td>
<td>9.7</td>
<td>161</td>
<td></td>
</tr>
<tr>
<td>2.5</td>
<td>4.0</td>
<td>67</td>
<td>6.5</td>
<td>10.5</td>
<td>174</td>
<td></td>
</tr>
<tr>
<td>3.0</td>
<td>4.6</td>
<td>80</td>
<td>7.0</td>
<td>11.3</td>
<td>188</td>
<td></td>
</tr>
<tr>
<td>3.5</td>
<td>5.6</td>
<td>94</td>
<td>7.5</td>
<td>12.1</td>
<td>201</td>
<td></td>
</tr>
<tr>
<td>4.0</td>
<td>6.4</td>
<td>107</td>
<td>8.0</td>
<td>12.9</td>
<td>214</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>7.2</td>
<td>121</td>
<td>8.5</td>
<td>13.7</td>
<td>228</td>
<td></td>
</tr>
<tr>
<td>5.0</td>
<td>8.0</td>
<td>134</td>
<td>9.0</td>
<td>14.5</td>
<td>241</td>
<td></td>
</tr>
</tbody>
</table>

Grade or Slope (Based on slope = tangent of angle × 100)

<table>
<thead>
<tr>
<th>%</th>
<th>degrees</th>
<th>%</th>
<th>degrees</th>
</tr>
</thead>
<tbody>
<tr>
<td>1%</td>
<td>0.0⁰</td>
<td>9%</td>
<td>5.1⁰</td>
</tr>
<tr>
<td>2%</td>
<td>1.2⁰</td>
<td>10%</td>
<td>5.7⁰</td>
</tr>
<tr>
<td>3%</td>
<td>1.8⁰</td>
<td>11%</td>
<td>6.3⁰</td>
</tr>
<tr>
<td>4%</td>
<td>2.3⁰</td>
<td>12%</td>
<td>6.8⁰</td>
</tr>
<tr>
<td>5%</td>
<td>2.9⁰</td>
<td>13%</td>
<td>7.4⁰</td>
</tr>
<tr>
<td>6%</td>
<td>3.4⁰</td>
<td>14%</td>
<td>8.0⁰</td>
</tr>
<tr>
<td>7%</td>
<td>4.0⁰</td>
<td>15%</td>
<td>8.5⁰</td>
</tr>
<tr>
<td>8%</td>
<td>4.6⁰</td>
<td>16%</td>
<td>9.1⁰</td>
</tr>
</tbody>
</table>

wheelchair athletes on wheelchair or arm ergometers, cross-country skiers on ski ergometers, and swimmers in swim flumes, on swim benches, or in a pool while tethered to weighted pulleys. Another consideration is the norms by which the participant will be evaluated. The Maximal Oxygen Consumption Test should be performed on the same ergometer as that which was used by those performers whose scores generated the norms. A practical consideration is the cost and ancillary objectives of the test. For example, a step bench is inexpensive but is not a specific mode for a swimmer. A cycle ergometer facilitates the measurement of blood pressure by clinicians but is not specific for walkers and joggers.

The treadmill has two basic units of measure: (1) speed and (2) slope or grade (Table 15.1). Maximal speeds (mph or km-h⁻¹) may vary with different treadmills from 12 mph (19.3 km-h⁻¹) to 15 mph (24 km-h⁻¹) to 25 mph (40.2 km-h⁻¹). The maximal slopes or grades of laboratory treadmills are about 25 %, but some can reach 40 % grade (= 22°). Table 15.1 provides the equivalent speeds in the American and metric systems, along with the slopes in degrees and percent grade.

Metabolic Measurement Equipment

Three variables—pulmonary ventilation ($V_e$) and the fractions of exhaled oxygen ($F_{e}O_2$) and carbon dioxide ($F_{e}CO_2$)—need to be continuously measured throughout the test in order to determine oxygen consumption and a variety of related metabolic variables (e.g., CO₂ production, respiratory exchange ratio). The measurement of pulmonary ventilation requires an air volume meter, which can either be part of an automated system (e.g., pneumotachometer, turbine) or a nonautomated piece of equipment (e.g., dry gas meter, tissot spirometer). Figure 15.1 demonstrates the components of a typical metabolic measurement system. Ventilation is most often measured during exhalation and is designated as exhaled ventilation ($V_e$). In some cases, usually when using a dry gas meter, it can also be measured during inhalation and is then referred to as inhaled ventilation ($V_i$). The recorded unit of measure for pulmonary ventilation is liters per minute (L·min⁻¹). To collect and sample the exhaled air, several auxiliary pieces of equipment are necessary. A respiratory valve (Figure 15.2) is a two-way valve that allows inhaled air to enter through one port (inlet port), but then directs all of the exhaled air through the opposite port (outlet port), where it enters a breathing tube or ventilatory hose. This particular tube or hose is flexible yet is corrugated or contains metal wire so that it does not collapse. The respiratory valve can be outfitted with a saliva trap that prevents saliva from entering the breathing tube. Typically, support is provided for the respiratory valve through the use of special headgear, or it can be supported from above (from an overhead rail or from the ceiling). A rubber mouthpiece similar to a scuba mouthpiece attaches to the respiratory valve. The flanges of the mouthpiece prevent the leakage of air around the participant’s mouth, while the protruding tabs allow gripping the mouthpiece with the teeth. A noseclip is worn to prevent inhalation and exhalation of air through the nose. Before the test, the air volume meter is calibrated with a special calibration syringe (Figure 15.3). The calibration syringe is specially designed and manufactured to provide an exact volume of air per stroke (e.g., 1 liter, 3 liters) and is used in the calibration of the metabolic measurement system (Box 15.2).

In addition to measuring the volume of air inhaled or exhaled, it is also necessary to measure the fractions of exhaled O₂ and CO₂, requiring an oxygen analyzer and a carbon dioxide analyzer. Many electronic oxygen analyzers are available, most of which use paramagnetic or galvanic fuel cell principles to determine the fractional (or percentage) concentration of oxygen in the exhaled air ($F_{e}O_2$). These analyzers are designed to be most accurate between oxygen concentrations of 15 % (0.15) and 21 % (0.21), which roughly corresponds to the values expected in exhaled air. Most carbon dioxide analyzers use an infrared principle to determine the fractional (or percentage) concentration of carbon dioxide ($F_{e}CO_2$). The reference standard for gas concentrations is the mass spectrometer, which can be used to analyze various gases. It is not frequently used in exercise physiology laboratories, however, because of its expense. A cylinder of calibration gas is used to regularly check the calibration of the gas analyzers. A typical calibration gas might consist of 16 % oxygen and 4 % carbon dioxide to simulate the values observed in exhaled air. The gas sample used for analysis during the exercise test can be drawn directly from the respiratory valve, or it can be drawn from a
Figure 15.1  Schematic of the components of an automated (computerized) metabolic measurement system for measuring ventilation (\(V_e\)) and the fractions of exhaled \(O_2\) (\(F_{\text{e}O_2}\)) and \(CO_2\) (\(F_{\text{e}CO_2}\)). In some cases, gas samples are drawn from the respiratory valve (instead of the mixing chamber) and \(V_e\) is measured with a turbine or spirometer (usually if nonautomated). Optionally, a dry gas meter can be used to measure inhaled (or exhaled) ventilation.

Figure 15.2  A two-way, non-rebreathing respiratory valve prevents air from exiting the same port that it entered.

mixing chamber (Figure 15.1). The mixing chamber, typically a Plexiglas™ cylinder or box with internal baffles, promotes mixing of the exhaled air such that a uniformly mixed sample of exhaled air can be drawn for analysis of \(F_{\text{e}O_2}\) and \(F_{\text{e}CO_2}\). Most automated systems draw the gas sample continuously from the exhaled air and then filter, dry, and warm it to account for the water vapor in the sample. The values of \(F_{\text{e}O_2}\) and \(F_{\text{e}CO_2}\) are then determined automatically and sent to the computer, where the metabolic variables are calculated and displayed at the desired time intervals (e.g., 15 s, 30 s, 1 min). When nonautomated systems are used, gas samples can be collected in small rubber bags ( aliquots) or can be drawn from large collection bags (e.g., Douglas bag, meteorological balloon) for analysis.

Exercise Protocol

The Maximal Oxygen Consumption Test usually requires the participant to exercise to exhaustion, although it need not be quite so stressful as long as the other traditional criteria are met. The exercise may be performed on various modalities, such as (a) step bench, (b) cycle ergometer, (c) treadmill, (d) swim flume, (e) wheelchair ergometer, (f) rowing ergometer, (g) skiing ergometer, and others. The test protocol, which consists of the prescription for time spent at each power level, is often a continuous and progressive type that eventually exceeds the aerobic power of the exerciser. Thus, the test includes submaximal, maximal,
**BOX 15.2** Calibration of Metabolic Instruments

Regular calibration of the metabolic instruments is essential for maintaining the reliability and validity of the VO₂max Test. It is best to follow the specific calibration instructions provided by the manufacturer of the equipment. However, some general calibration guidelines can be recommended. The instruments should be powered up and allowed to warm up for at least 30 min (or longer) prior to beginning any calibration. The equipment used for measuring meteorological conditions (i.e., thermometer, barometer, and hygrometer) should also be periodically calibrated.

Calibration procedures typically call for the calibration of three instruments, the air volume meter, the oxygen analyzer, and the carbon dioxide analyzer. It is assumed in this manual that a metabolic measurement system (or metabolic cart) is being used, so the calibration procedures in this case apply to the system as a whole. However, laboratories without an automated system will need to calibrate each component individually.

The instrument for measuring air volume (pulmonary ventilation) differs from system to system, but the most common is the pneumotachometer or turbine. These devices are calibrated by passing a specific volume of air through them with the use of a calibration syringe (Figure 15.3). This syringe is carefully manufactured so that one stroke delivers an exact volume of air (i.e., 1, 3, or 5 liters). Calibration of the air volume meter typically need not be done prior to every test but should be done daily or at least weekly.

Calibration of the gas analyzers requires a standardized calibration gas with known concentrations of O₂ and CO₂ determined by mass spectrometry (the "gold standard"). These calibration gases typically come with the metabolic measurement system or are available from a commercial gas vendor. It is typical to calibrate both analyzers against these standard gases prior to each exercise test. A two-point calibration (zero or low range and high range) is most common, but some authorities recommend a three-point calibration (zero, midrange, and high range).³⁶

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**Table 15.2** Cycle Ergometer Protocols for Measuring VO₂max

<table>
<thead>
<tr>
<th>Warm-up</th>
<th>Below average fitness</th>
<th>Average fitness</th>
<th>Above average fitness</th>
</tr>
</thead>
<tbody>
<tr>
<td>0:00-5:00</td>
<td>25 W</td>
<td>75 W</td>
<td>150 W</td>
</tr>
<tr>
<td>Exercise</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0:00-2:00</td>
<td>50 W</td>
<td>100 W</td>
<td>175 W</td>
</tr>
<tr>
<td>2:00-4:00</td>
<td>75 W</td>
<td>125 W</td>
<td>200 W</td>
</tr>
<tr>
<td>4:00-6:00</td>
<td>100 W</td>
<td>150 W</td>
<td>225 W</td>
</tr>
<tr>
<td>6:00-8:00</td>
<td>125 W</td>
<td>175 W</td>
<td>250 W</td>
</tr>
<tr>
<td>8:00-10:00</td>
<td>150 W</td>
<td>200 W</td>
<td>275 W</td>
</tr>
<tr>
<td>10:00-12:00</td>
<td>175 W</td>
<td>225 W</td>
<td>300 W</td>
</tr>
<tr>
<td>12:00-14:00</td>
<td>200 W</td>
<td>250 W</td>
<td>325 W</td>
</tr>
<tr>
<td>Recovery</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>0:00-2:00</td>
<td>50-75 W</td>
<td>50-75 W</td>
<td>125-200 W</td>
</tr>
</tbody>
</table>

---

**Cycling Protocols**

Before the test, the estimated VO₂max of the participant from previous field tests helps in determining the proper protocol. If no prior tests exist, then questioning the participant about training habits is helpful.

The cycle protocols presented in Table 15.2 are modifications of a former continuous protocol³⁹ and are based on the aerobic fitness status of the participant. They are for persons who are estimated to have below average, average, or above average aerobic fitness. For persons with below average fitness, the initial power level is 50 W and increases by 25 W for subsequent 2 min power intervals. A similar protocol is followed for persons with average levels of aerobic fitness, except that the initial power level is 100 W. For persons with suspected VO₂max levels that are exceptionally high, the starting power level can be 175 W in order to keep the duration of the test close to a 9 min maximum. For some elite cyclists who could reach 450 W, the test duration would be 30 min if they started at 175 W; so an even higher starting power or a larger increase in power per stage may be appropriate. Oxygen consumption can be estimated for cycling as seen in Table 15.3. Although economy or efficiency of cycling may vary with pedal rpm during submaximal exercise,¹⁶,²⁹,⁴⁸,⁴⁹,⁵⁸,⁶³ it does not mean that rpm will necessarily alter the peak or maximal oxygen consumption.⁵¹

**Treadmill Protocol**

It appears that similar results are obtained with a variety of treadmill protocols, although some take less time than others.²⁴ One of the most popular treadmill tests is the Bruce Test, the earliest standard treadmill test.⁴² Although it is often used for cardiovascular screening purposes,¹² it is also a common protocol for predicting¹,¹²,⁵⁸ and directly measuring maximal oxygen consumption.⁴⁶
### Table 15.3

**Estimation of Relative Oxygen Consumption from Cycle Power (W)**

<table>
<thead>
<tr>
<th>Power (W)</th>
<th>VO₂ Body Weight (mL·kg⁻¹·min⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>200</td>
<td>200</td>
</tr>
<tr>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>400</td>
<td>400</td>
</tr>
<tr>
<td>500</td>
<td>500</td>
</tr>
</tbody>
</table>

### Table 15.4

**Bruce Treadmill Protocol with Estimated VO₂ (mL·kg⁻¹·min⁻¹)**

<table>
<thead>
<tr>
<th>Standard</th>
<th>Bruce</th>
<th>Modified</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Grade</td>
<td>V̇O₂</td>
<td>Speed</td>
<td>Grade</td>
</tr>
<tr>
<td>0</td>
<td>0.00-600</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>1</td>
<td>1.0-900</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>2.0-1200</td>
<td>2</td>
<td>2</td>
</tr>
<tr>
<td>3</td>
<td>3.0-1500</td>
<td>3</td>
<td>3</td>
</tr>
<tr>
<td>4</td>
<td>4.0-1800</td>
<td>4</td>
<td>4</td>
</tr>
<tr>
<td>5</td>
<td>5.0-2100</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>6.0-2400</td>
<td>6</td>
<td>6</td>
</tr>
<tr>
<td>7</td>
<td>7.0-2700</td>
<td>7</td>
<td>7</td>
</tr>
<tr>
<td>8</td>
<td>8.0-3000</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>9</td>
<td>9.0-3300</td>
<td>9</td>
<td>9</td>
</tr>
<tr>
<td>10</td>
<td>10.0-3600</td>
<td>10</td>
<td>10</td>
</tr>
</tbody>
</table>

### Notes

- The Bruce protocol (Table 15.4) consists of seven 3-min stages. Most protocols usually last 3 min, although the initial stage is 1 min.
- The initial 90 s of the first stage are critical for determining heart rate. Although the stages are divided into 3 min, they are sometimes divided into 1 min.
- The VO₂ max is determined during the final stage.
- The protocol is modified for patients with reduced VO₂ max.

---

**Criteria for Establishing Maximal Oxygen Consumption**

Part of the protocol is to establish whether or not the participant reached maximal oxygen consumption. To do this, VO₂ max should elicit an increase in VO₂ of 4 mL·kg⁻¹·min⁻¹ or more during the last 3 min of exercise. The increase in VO₂ during the final stage is usually greater than 2.5 mL·kg⁻¹·min⁻¹.

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**Historical Notes**

G. R. F. H. and J. P. B. M. 1969. The Bruce and modified Bruce protocols have been used since the late 1960s, with some modifications. The protocols have evolved over the years, and different versions have been used by various investigators.

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**References**


James et al. 1975. The modified Bruce protocol: A comparison with the standard protocol.


---

**Acknowledgments**

The authors wish to thank the following individuals for their contributions to this work: Dr. J. P. B. M., Dr. G. R. F. H., and Dr. W. J. S. A. for their insights and expertise in the development of the protocols. The modified Bruce protocol was developed in collaboration with Dr. G. R. F. H. and Dr. J. P. B. M., while the original Bruce protocol was developed by Dr. W. J. S. A.
levels, possibly due to increased lactate and hydrogen ion concentration, increased muscle temperature, and/or recruitment of less efficient fast-twitch muscle fibers. In summary, the presence of a plateau (however defined) in VO\textsubscript{2} at the end of a graded exercise test to exhaustion provides support for the test being maximal. However, the absence of a plateau does not necessarily discount the VO\textsubscript{2} as maximal.

Several other "secondary" physiological criteria may be applied in the presence or absence of a plateau in oxygen consumption. The first is a respiratory exchange ratio (RER) in excess of 1.05,\textsuperscript{22} 1.10,\textsuperscript{24,41} or 1.15.\textsuperscript{2,3,5,35} A high RER (≥1.00) indicates an increase in carbon dioxide production proportionately greater than the related increase in oxygen consumption. The accelerated CO\textsubscript{2} production is a result of the buffering of hydrogen ions produced near the end of a graded exercise test. At this point, aerobic metabolism nears its maximal rate and anaerobic energy production becomes necessary to maintain the very high intensity over the last several minutes of the test. In general, the higher the RER the more likely the effort was maximal, so it may be appropriate to use the highest criterion (RER ≥ 1.15). Another criterion is a venous blood lactate concentration in excess of 8 mM·L\textsuperscript{-1},\textsuperscript{2,3,5,35} or 10 mM·L\textsuperscript{-1}.\textsuperscript{41} These values are 8–10 times the typical blood lactate concentration at rest (1 mM·L\textsuperscript{-1}). Blood lactates this high indicate the intense nature of the exercise and the heavy contribution required of the lactic acid system. Because of the need for blood sampling, however, this specific criterion is more difficult to assess. A final physiological variable to consider is heart rate. Although there is considerable variability in maximal heart rate, as indicated by a standard deviation of 10–12 bpm, it is reliable and reproducible within individuals. If during an exercise test where VO\textsubscript{2} is being directly measured, the participant reaches a previously measured maximal heart rate, it can be assumed that the VO\textsubscript{2} reached will also be maximal. In cases where maximal heart rate has not been previously determined, a maximal heart rate predicted from age (220 – Age) may be used. In assessing whether a test is maximal it is preferred that exercise heart rate meet this predicted HR\textsubscript{max}, but other sources consider an exercise heart rate within 12 bpm\textsuperscript{24} or 10 bpm\textsuperscript{3,5,67} of predicted HR\textsubscript{max} as evidence of maximal effort.

With regard to the psychological criteria, the participant is typically instructed to give a maximal effort, to exercise to exhaustion, to run or cycle until he or she can go no longer. This requires a high degree of motivation. To help quantify and allow for a more objective assessment of exertion, the participant typically provides a rating of perceived exertion (RPE) throughout the graded exercise test. The RPE scale (Table 15.5) integrates a variety of signals from the body—cardiovascular, respiratory, muscular, and nervous systems—into a general whole sensation that allows the participant to provide a perception of the intensity of exertion. The original Borg 15-category RPE scale,\textsuperscript{7} ranging from the lowest level of exertion, 6, to the highest level of exertion, 20, is based on the linear relationship between exertion, power output, and heart rate.\textsuperscript{47} It was later revised with ratio properties based on the nonlinear properties of psychophysical and some physiologic variables, such as blood lactate and ventilation,\textsuperscript{2} and was renamed the Borg 10-category ratio (CR-10) RPE scale.\textsuperscript{8} This newer category-ratio scale (CR-10) may be more suitable for determining subjective symptoms associated with breathing, aches, and pains and is highly correlated with blood lactate.\textsuperscript{8,62} The choice of which scale to use is up to the tester. An RPE > 17\textsuperscript{2} or an RPE of 19 or 20\textsuperscript{41} have been recommended as indicating a maximal effort.

### Procedures for the Maximal Oxygen Consumption Test

The initial steps for the VO\textsubscript{2max} Test consist of calibrating the ergometer and metabolic instruments, selecting an exercise mode and protocol, and preparing the participant for the exercise test.

### Preparation

As with the other aerobic tests, the participant should be well rested and refrain from prior exercise the day of testing, should not eat a large meal within 2–3 hours of the test, and should be normally hydrated and refrain from consuming or taking any stimulants. The technician (tester) prepares for the test by completing the following steps.

1. Periodically calibrate the ergometer being used (e.g., treadmill, cycle ergometer).
2. Calibrate the metabolic measurement system (review Box 15.2) according to the manufacturer's specifications.

---

**Table 15.5** Borg Rating of Perceived Exertion (RPE) Scale

<table>
<thead>
<tr>
<th>Original Category-Ratio Scale (6–20)</th>
<th>Modified Category-Ratio (CR-10) Scale (0–10)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6</td>
<td>0 Nothing at all</td>
</tr>
<tr>
<td>7 Very, very light</td>
<td>0.5 Very, very weak</td>
</tr>
<tr>
<td>8</td>
<td>(just noticeable)</td>
</tr>
<tr>
<td>9 Very light</td>
<td>1 Very weak</td>
</tr>
<tr>
<td>10 Light</td>
<td>2 Weak</td>
</tr>
<tr>
<td>11</td>
<td>3 Moderate</td>
</tr>
<tr>
<td>12</td>
<td>4 Somewhat strong</td>
</tr>
<tr>
<td>13</td>
<td>5 Strong</td>
</tr>
<tr>
<td>14</td>
<td>6</td>
</tr>
<tr>
<td>15 Heavy</td>
<td>7 Very strong</td>
</tr>
<tr>
<td>16</td>
<td>8</td>
</tr>
<tr>
<td>17 Very heavy</td>
<td>9</td>
</tr>
<tr>
<td>18</td>
<td>10 Very, very strong</td>
</tr>
<tr>
<td>19 Very, very heavy</td>
<td>10 (almost maximal)</td>
</tr>
<tr>
<td>20</td>
<td>10+ Maximal</td>
</tr>
</tbody>
</table>

*Sources: From Borg (1970)\textsuperscript{7} and Borg (1982).\textsuperscript{8}*

---

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3. Measure and record the participant's basic data (name, age, height, and body weight) along with the meteorological data (temperature, barometric pressure, and relative humidity) on Form 15.2.

4. Establish the desired exercise mode and protocol to be used during the test. Orient the participant by explaining the purpose and protocol of the Maximal Oxygen Consumption Test.

5. If heart rate is to be determined by electrocardiography (ECG) or heart-rate monitor, prepare and attach the required equipment (e.g., ECG electrodes, heart-rate transmitter). Likewise, if blood pressure is to be recorded, prepare and attach all necessary equipment. *(Note: Blood drawing equipment would also be prepared at this point if blood lactate measurement is desired. No further description of blood drawing technique or analysis is included in this manual.)*

6. Instruct the participant on the proper use of the ergometer (e.g., how to mount and dismount the moving treadmill belt, how to maintain pedaling form and rate on the cycle ergometer). If using a treadmill, it is especially important to prevent injury by instructing the participant on how to grab the rails and dismount the treadmill at the point of exhaustion.

7. Instruct the participant on proper use of the rating of perceived exertion (RPE) scale.

8. Instruct the participant on hand signals that may be used during the test (e.g., a thumbs-up sign indicating the desire to continue) due to the inability to speak because of the mouthpiece and respiratory equipment.

9. Have the participant complete an appropriate warm-up before the test. Little warm-up is needed if the protocol begins at a low level to allow the collection of submaximal data. More warm-up is indicated if the protocol starts at a higher level with less emphasis on submaximal data collection.

**Procedures During the Exercise Test**

Typically more than one technician is involved during the test. If this is the case, each technician needs to know his or her specific duties and responsibilities and carry them out correctly during the test. The procedures for the $\dot{V}O_2\text{max}$ test are as follows:

1. Attach all necessary equipment (e.g., headgear for support of respiratory valve) and optional equipment (e.g., heart-rate monitor, ECG lead wires); insert the mouthpiece of the respiratory valve into the participant's mouth; attach the breathing tube to the "out" port of the valve; and affix the noseclip to the participant's nose *(do not forget the noseclip)*.

2. Instruct the participant to begin exercising at the initial stage of the exercise test protocol.

3. Simultaneously start all equipment (e.g., metabolic measurement system, ECG, heart-rate monitor) and timers.

4. If an automated metabolic measurement system is being used (which is assumed), all metabolic data are measured, displayed, and recorded automatically for the duration of the test. If a semiautomated or manual system is being used (for instructional purposes), each technician records a specific variable (e.g., ventilation, $F_{E}O_2$, $F_{E}CO_2$, heart rate) at specific intervals (e.g., 15 s, 30 s, 1 min) throughout the test.

5. Follow the test protocol by increasing treadmill speed and/or grade or cycle ergometer power at the appropriate times (if not done automatically by the ergometer). Record any desired data (not recorded automatically) at specific intervals. It is typical to record heart rate each minute; RPE at 1, 2, or 3 min intervals; and if recording the ECG or blood pressure, they are typically recorded at 3 min intervals (but this can vary based on the protocol).

6. Monitor the participant for any signs or symptoms that could warrant stopping the test prematurely (e.g., chest pain, leg pain, ECG changes, blood pressure changes, dizziness, nausea).

7. Determine when the participant is approaching a maximal effort through the use of heart rate (approaching a previously measured HRmax or within 10 beats of age-predicted HRmax); respiratory exchange ratio (approaching an RER of 1.15 or above); rating of perceived exertion (approaching an RPE of 18 or above); and other observations (e.g., participant no longer gives thumbs-up sign, changes in treadmill gait, changes in cycling mechanics).

8. When signs of maximal effort begin to appear, encourage the participant to continue as long as possible without jeopardizing safety. If the test is being done on a treadmill, a spotter should be used to assist the participant to reduce the likelihood of injury.

9. When the participant voluntarily stops at what is assumed to be the point of exhaustion, safely end the test. As quickly as possible, begin a cool-down. It is important that the participant spend minimal time standing still on the treadmill belt or sitting still on the cycle ergometer, because of the possibility of blood pooling in the legs.

10. Remove all equipment. Discard any disposable equipment (e.g., electrodes), and clean and sanitize all reusable equipment (e.g., mouthpiece, noseclip, respiratory valve, breathing tube, heart-rate monitor, blood pressure cuff) according to accepted practices. Various forms of disinfection (e.g., Cidex™, iodine, bleach, etc.) may be considered.

**Calculation of Oxygen Consumption and Related Variables**

It is assumed in this manual that in most cases an automated system will be used to measure, record, and display oxygen consumption and a variety of related variables throughout the exercise test, as seen in Figure 15.4.
Figure 15.4. Sample data from graded exercise test showing: (a) ventilation, (b) $F_{O_2}$ and $F_{CO_2}$, (c) oxygen consumption, (d) CO$_2$ production, (e) respiratory exchange ratio, (f) % energy from carbohydrate and fat, (g) energy expenditure from carbohydrate and fat, and (h) heart rate.
However, an important concept in this chapter is how the raw data (\( V_E \), \( F_EO_2 \), and \( F_ECO_2 \)) are used mathematically to derive the desired physiological results. For this reason, what follows is a detailed discussion of the necessary mathematical calculations.

**Ventilation and Ambient/Standard Conditions**

The first variable of interest in calculating oxygen consumption is the pulmonary ventilation or, simply, ventilation. Ventilation is typically measured on exhalation by collecting all of the air exhaled or expired by the participant. When ventilation is measured during exhalation it is referred to as exhaled ventilation or the total volume of air exhaled from the lungs per minute (abbreviated as \( \dot{V}_E \)). Ventilation may also be measured by measuring the inhaled ventilation or the total volume of air inspired into the lungs per minute (\( \dot{V}_I \)).

Ventilation (\( V_E \)), like any other air volume or lung volume (e.g., vital capacity), is subject to the gas laws, meaning that it is affected by the ambient (surrounding) conditions. The two biggest factors that affect \( V_E \) are temperature and pressure (i.e., barometric pressure). Consider the effect that these two factors have on the volume (size) of a balloon. If a balloon is warmed, the movement of the air molecules inside the balloon increases and they exert more pressure on the walls of the balloon, causing it to increase in size (expand). If cooled, the molecular movement decreases, exerting less pressure and causing it to decrease in size (shrink). When the pressure surrounding the balloon changes, it inversely affects the volume. That is, a drop in surrounding (barometric) pressure allows the balloon to expand, while a rise in pressure squeezes the balloon, causing it to shrink.

Two specific sets of atmospheric conditions affecting ventilation and other air and lung volumes are referred to as **ambient conditions** and **standard conditions**. Ambient conditions are the surroundings under which air volumes are measured. The conditions apply to three variables: temperature, pressure, and saturation. For this reason, the abbreviation ATSP, for ambient temperature, pressure, saturated, is used for ambient conditions. Ambient (or room) temperature and barometric pressure vary and must be measured and recorded at the time of the exercise test to be used in the calculation of oxygen consumption. Air exhaled from the lungs is assumed to be fully saturated with water vapor; thus when \( V_E \) is measured under ATSP conditions, it is assumed to be saturated. Standard conditions refer to a universally designated set of conditions that have been determined to consist of a standard temperature of 0°C (or 273 K) and a standard pressure of 760 mm Hg (typical barometric pressure at sea level, also equal to 1013 hPa), with the air or gas assumed to be dry; hence, the abbreviation STPD, for standard temperature, pressure, dry.

Oxygen consumption is (nearly) always expressed under STPD conditions. This allows all \( VO_2\max \) values recorded under any ambient conditions, regardless of ambient temperature or barometric pressure, to be expressed in the same standard conditions, allowing for direct comparisons. An STPD correction factor (CF) can be calculated for a given set of ambient conditions, and then that STPD CF is used to correct \( V_E \) from ATSP to STPD conditions. The STPD CF is calculated taking into consideration ambient temperature, barometric pressure, the vapor pressure of water at ambient temperature (a lower temperature decreases the amount of water vapor pressure in the expired air), standard temperature (0°C or 273 K), and standard pressure (760 mm Hg or 1013 hPa). The vapor pressure of water (\( P_{H_2O} \)) varies with ambient temperature, as seen in Table 15.6. The STPD correction factor is calculated by using Equation 15.1. Note that 273 is added to each temperature (°C) to convert it into the Kelvin scale, which is necessary for the calculation.

\[
\text{STPD CF} = \frac{[T_{STD} \text{ (°C)} + 273 \text{ K}]}{[T_A \text{ (°C)} + 273 \text{ K}]} \times \frac{[P_B \text{ (mm Hg)} - P_{H_2O \text{ at } T_A}]}{[P_{STD}]} \tag{Eq. 15.1}
\]

*Where:* \( T_{STD} \): Standard temperature (0°C)
*Where:* \( T_A \): Ambient temperature (varies)
*Where:* \( P_B \): Barometric pressure (varies)
*Where:* \( P_{H_2O} \): Vapor pressure of water at \( T_A \) (varies)
*Where:* \( P_{STD} \): Standard pressure (760 mm Hg)

**Example:** If the ambient conditions are as follows: \( T_A = 24°C \), \( P_B = 756 \text{ mm Hg} \); and \( P_{H_2O} = 22 \text{ mm Hg} \); then the STPD CF for correcting any volume from ambient conditions (ATPS) to standard conditions (STPD) would be 0.888, as seen in Equation 15.2a and Table 15.7. A pulmonary ventilation (\( V_E\text{,ATPS} \)) of 100 L·min⁻¹ measured under ambient conditions (ATPS) is corrected to standard conditions (STPD) by multiplying by the STPD CF, with the result being \( \dot{V}_E\text{,STPD} = 88.8 \text{ L·min}^{-1} \) (Eq. 15.2b).

\[
\text{STPD CF} = \frac{[0 \text{ °C} + 273 \text{ K}]}{[24°C + 273 \text{ K}]} \times \frac{[756 \text{ mm Hg} - 22 \text{ mm Hg}]}{[760 \text{ mm Hg}]} = 0.888 \tag{Eq. 15.2a}
\]
### Table 15.7 Correction Factors for Reducing Volumes from Ambient to Standard Conditions

<table>
<thead>
<tr>
<th>Barometric Pressure (mm Hg)</th>
<th>20</th>
<th>21</th>
<th>22</th>
<th>23</th>
<th>24</th>
<th>25</th>
<th>26</th>
<th>27</th>
<th>28</th>
</tr>
</thead>
<tbody>
<tr>
<td>740</td>
<td>0.083</td>
<td>0.081</td>
<td>0.087</td>
<td>0.083</td>
<td>0.081</td>
<td>0.087</td>
<td>0.083</td>
<td>0.081</td>
<td>0.087</td>
</tr>
<tr>
<td>742</td>
<td>0.086</td>
<td>0.083</td>
<td>0.089</td>
<td>0.086</td>
<td>0.083</td>
<td>0.089</td>
<td>0.086</td>
<td>0.083</td>
<td>0.089</td>
</tr>
<tr>
<td>744</td>
<td>0.090</td>
<td>0.086</td>
<td>0.092</td>
<td>0.090</td>
<td>0.086</td>
<td>0.092</td>
<td>0.090</td>
<td>0.086</td>
<td>0.092</td>
</tr>
<tr>
<td>746</td>
<td>0.093</td>
<td>0.088</td>
<td>0.094</td>
<td>0.093</td>
<td>0.088</td>
<td>0.094</td>
<td>0.093</td>
<td>0.088</td>
<td>0.094</td>
</tr>
<tr>
<td>748</td>
<td>0.095</td>
<td>0.091</td>
<td>0.096</td>
<td>0.095</td>
<td>0.091</td>
<td>0.096</td>
<td>0.095</td>
<td>0.091</td>
<td>0.096</td>
</tr>
<tr>
<td>750</td>
<td>0.097</td>
<td>0.093</td>
<td>0.098</td>
<td>0.097</td>
<td>0.093</td>
<td>0.098</td>
<td>0.097</td>
<td>0.093</td>
<td>0.098</td>
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<tr>
<td>752</td>
<td>0.099</td>
<td>0.096</td>
<td>0.099</td>
<td>0.099</td>
<td>0.096</td>
<td>0.099</td>
<td>0.099</td>
<td>0.096</td>
<td>0.099</td>
</tr>
<tr>
<td>754</td>
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<td>0.100</td>
<td>0.098</td>
<td>0.100</td>
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<tr>
<td>756</td>
<td>0.102</td>
<td>0.098</td>
<td>0.102</td>
<td>0.102</td>
<td>0.098</td>
<td>0.102</td>
<td>0.102</td>
<td>0.098</td>
<td>0.102</td>
</tr>
<tr>
<td>758</td>
<td>0.104</td>
<td>0.100</td>
<td>0.104</td>
<td>0.104</td>
<td>0.100</td>
<td>0.104</td>
<td>0.104</td>
<td>0.100</td>
<td>0.104</td>
</tr>
<tr>
<td>760</td>
<td>0.106</td>
<td>0.100</td>
<td>0.106</td>
<td>0.106</td>
<td>0.100</td>
<td>0.106</td>
<td>0.106</td>
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<tr>
<td>762</td>
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<td>0.100</td>
<td>0.108</td>
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<td>0.108</td>
<td>0.108</td>
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<td>0.108</td>
</tr>
<tr>
<td>764</td>
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<td>0.100</td>
<td>0.110</td>
<td>0.110</td>
<td>0.100</td>
<td>0.110</td>
<td>0.110</td>
<td>0.100</td>
<td>0.110</td>
</tr>
</tbody>
</table>

Note: STPD CF = [(273 K) / (T_s + 273 K)] * (P_b - P_H2O at T_s) / (760 mm Hg); T_s = Ambient temperature; P_b = Barometric pressure; P_H2O = Vapor pressure of water at ambient temperature.

\[
\dot{V}_{E \text{STPD}} \text{ (L min}^{-1}) = \dot{V}_{E \text{ATPS}} \text{ (L min}^{-1}) \times \text{STPD CF} = 100 \times 0.888 = 88.8 \text{ L min}^{-1}
\]

**Eq. 15.2b**

### Oxygen Consumption

Three specific variables—pulmonary ventilation expressed in STPD conditions (\(\dot{V}_{E \text{STPD}}\)), and the fractions (or percentages) of exhaled or expired oxygen (\(F_{E O_2}\)) and carbon dioxide (\(F_{E CO_2}\))—must be continuously measured and recorded throughout the exercise test for the purpose of calculating submaximal and maximal oxygen consumption and other related metabolic variables. Oxygen consumption, or the volume of oxygen being consumed by the body per minute (\(\dot{VO}_2\)), is literally the difference between the volume of oxygen being inhaled into the body (\(\dot{V}_{O_2} \text{ inspired}\)) and the volume being exhaled from the body (\(\dot{V}_{E O_2}\)). This is the basis of the derivation of a mathematical equation to be used to calculate oxygen consumption beginning with Equations 15.3a and 15.3b. By knowing the fraction (or percentage) of a total volume that is made up by a particular gas (i.e., \(O_2\), \(CO_2\), or \(N_2\)), it is possible to determine the specific volumes of inspired and expired gases. Given Equations 15.3c and 15.3d, substitution into Equation 15.3b yields Equation 15.3e.

Given: \(\dot{VO}_2 = [\dot{VO}_2 \text{ Inspired}] - [\dot{VO}_2 \text{ Expired}]\)  \[[\text{Eq. 15.3a}]\]

Given: \(\dot{VO}_2 = [\dot{V}_1 \text{ O}_2] - [\dot{V}_{E} \text{ O}_2]\)  \[[\text{Eq. 15.3b}]\]

Where: \(\dot{V}_1 \text{ O}_2\): Volume of inspired \(O_2\)

Where: \(\dot{V}_{E} \text{ O}_2\): Volume of expired \(O_2\)

Given: \(\dot{V}_1 \text{ O}_2 = \dot{V}_1 \times F_{I O_2}\)  \[[\text{Eq. 15.3c}]\]

Where: \(\dot{V}_1\): Volume of inspired air

Where: \(F_{I O_2}\): Fraction of inspired \(O_2\)

**Given:** \(\dot{V}_{E} \text{ O}_2 = \dot{V}_{E} \times F_{E O_2}\)  \[[\text{Eq. 15.3d}]\]

Where: \(\dot{V}_{E}\): Volume of expired air

Where: \(F_{E O_2}\): Fraction of expired \(O_2\)

**Substitution yields:** \(\dot{VO}_2 = [\dot{V}_1 \times F_{I O_2}] - [\dot{V}_{E} \times F_{E O_2}]\)  \[[\text{Eq. 15.3e}]\]

The next step in the derivation of the desired mathematical equation is a brief comment on nitrogen and the relationship between the total volume of air inhaled into the lungs (\(\dot{V}_1\)) and that exhaled from the lungs (\(\dot{V}_{E}\)). It is commonly assumed that nitrogen (\(N_2\)) is neither consumed nor produced by humans. For this reason, it can also be assumed that the volume of nitrogen inhaled (\(\dot{V}_1 N_2\)) is equal to the volume exhaled (\(\dot{V}_{E} N_2\)), as seen in Equation 15.4a. Based on the given values in Equations 15.4b and 15.4c, and again as a product of substitution, the result is Equation 15.4d. Equation 15.4d can then be transposed to solve for \(\dot{V}_1\) (Eq. 15.4e), which is important, because this allows the measurement of only exhaled or expired volumes (\(\dot{V}_{E}\)) and does not require the additional work of also measuring the inhaled or inspired volumes (\(\dot{V}_1\)).

**Assume:** \(\dot{V}_1 N_2 = \dot{V}_{E} N_2\)  \[[\text{Eq. 15.4a}]\]

Where: \(\dot{V}_1 N_2\): Volume of inspired \(N_2\)

Where: \(F_{I N_2}\): Fraction of inspired \(N_2\)

**Given:** \(\dot{V}_1 N_2 = \dot{V}_1 \times F_{I N_2}\)  \[[\text{Eq. 15.4b}]\]

**Given:** \(\dot{V}_{E} N_2 = \dot{V}_{E} \times F_{E N_2}\)  \[[\text{Eq. 15.4c}]\]

Where: \(\dot{V}_{E} N_2\): Volume of expired \(N_2\)

Where: \(F_{E N_2}\): Fraction of expired \(N_2\)

**Substitution yields:** \(\dot{V}_1 = [\dot{V}_1 \times F_{I N_2}] / \dot{V}_{E} N_2\)  \[[\text{Eq. 15.4d}]\]

**Transposition yields:** \(\dot{V}_1 = (\dot{V}_{E} \times F_{E N_2}) / \dot{V}_{E} N_2\)  \[[\text{Eq. 15.4e}]\]
The final steps involved in deriving the desired mathematical equation for calculating VO₂ involve substituting Equation 15.4e into Equation 15.3e to yield Equation 15.5a. Then one final step, substituting the assumed values of F₁N₂ and F₁O₂ (Eq. 15.5b), yields the desired equation (Eq. 15.5c). Typically the calculation of F₁N₂ (Eq. 15.5d) is done separately, but can also be substituted into Equation 15.5c if desired, resulting in one combined equation.

Substitution yields: \[ \dot{V}_O₂ = \left[ \dot{V}_E \times F₁N₂ \right] \times \left( F₁O₂ \right) \]
\[ \dot{V}_E \times F₁N₂ \]
\[ \text{Eq. 15.5a} \]

Given: \( F₁N₂ = 0.7993 \), and \( F₁O₂ = 0.2093 \)
\[ \text{Eq. 15.5b} \]

Substitution yields: \[ \dot{V}_O₂ = \left[ \left( \dot{V}_E \times F₁N₂ \right) \times \left( 0.2648 \right) \right] \times \left( F₁O₂ \right) \]
\[ \dot{V}_E \times F₁N₂ \]
\[ \text{Eq. 15.5c} \]

Where: \( F₁N₂ = 1.00 \) - \( (F₁O₂ + F₁CO₂) \)
\[ \text{Eq. 15.5d} \]

**Example:** A person with a \( \dot{V}_E \times F₁N₂ = 100 \text{ L-min}^{-1} \), \( F₁O₂ = 0.1750 \) (17.5 %), \( F₁CO₂ = 0.0375 \) (3.75 %), and therefore \( F₁N₂ = 0.7875 \) (78.75 %), would have an absolute \( \dot{V}_O₂ \) of 3.35 L-min\(^{-1}\), as seen in Equation 15.6.

\[ \dot{V}_O₂ = \left[ \left( 100 \times 0.7875 \right) \times \left( 0.2648 \right) \right] - \left[ \left( 100 \times 0.1750 \right) \right] = 20.85 - 17.50 = 3.35 \text{ L-min}^{-1} \]
\[ \text{Eq. 15.6} \]

**Relative Oxygen Consumption**

The oxygen uptake calculated in Equation 15.6 is considered an absolute oxygen uptake (expressed in L-min\(^{-1}\)). This value is important because it is used to calculate respiratory exchange ratio and energy expenditure. However, when using \( \dot{V}_O₂ \times \text{max} \) to express someone’s aerobic fitness, it is more common to express it on a relative basis per kg of body weight yielding a relative oxygen consumption. This is calculated by converting the absolute \( \dot{V}_O₂ \) from liters to milliliters by multiplying by 1000 (ml-L\(^{-1}\)), then dividing by body weight (kg), as seen in Equation 15.7a.

**Example:** If the same participant above (with an absolute \( \dot{V}_O₂ \) of 3.35 L-min\(^{-1}\)) weighs 80 kg, the relative \( \dot{V}_O₂ \) would be 41.9 ml-kg\(^{-1}\)-min\(^{-1}\) (Eq. 15.7b).

Relative \( \dot{V}_O₂ \) (ml-kg\(^{-1}\)-min\(^{-1}\))
\[ = \left( \dot{V}_O₂ \times 1000 \right) / \text{Body weight (kg)} \]
\[ \text{Eq. 15.7a} \]

Relative \( \dot{V}_O₂ = 3.35 \text{ L-min}^{-1} \times 1000 / 80 \text{ kg} = 41.9 \text{ ml-kg}^{-1} \text{-min}^{-1} \]
\[ \text{Eq. 15.7b} \]

**Carbon Dioxide Production**

With increasing exercise intensity, there is an increase not only in \( \dot{V}_O₂ \), but also in carbon dioxide production (\( \dot{VCO₂ \)) as a by-product of elevated aerobic metabolism. The measurement of \( \dot{VCO₂ \) is important because it allows for the subsequent calculation of the respiratory exchange ratio (RER). \( \dot{VCO₂ \) is the difference between the volume of CO₂ exhaled from the lungs and the volume of CO₂ inhaled into the lungs (Eq. 15.8a), which can also be expressed as in Equation 15.8b. If it is assumed that the volume of CO₂ inhaled into the lungs is negligible (since \( F₁CO₂ = 0.0003 \)), the equation reduces to Equation 15.8c. And finally, because the volume of exhaled CO₂ is the product of the exhaled ventilation and the fraction of CO₂ (Eq. 15.8d), this may be substituted to yield the equation used to mathematically calculate \( \dot{VCO₂ \) (Eq. 15.8e).

Given: \( \dot{VCO₂ = \dot{V}_E \times F₁CO₂ \) (Eq. 15.8a)

**Example:** A person with a \( \dot{V}_E \times F₁N₂ = 100 \text{ L-min}^{-1} \) and \( F₁CO₂ = 0.0375 \) (3.75 %), would have a \( \dot{VCO₂ \) of 3.75 L-min\(^{-1}\), as seen in Equation 15.9.

\[ \dot{VCO₂ = [100 \times 0.0375] = 3.75 \text{ L-min}^{-1} \]
\[ \text{Eq. 15.9} \]

**Respiratory Exchange Ratio**

RER, the ratio of carbon dioxide production to oxygen consumption, is calculated by dividing \( \dot{VCO₂ \) by \( \dot{V}_O₂ \) (Eq. 15.10a). Based on the previous examples, if \( \dot{VCO₂ \) = 3.75 L-min\(^{-1}\) and \( \dot{V}_O₂ \) = 3.35 L-min\(^{-1}\), then RER would be calculated as 1.12 (Eq. 15.10b).

**Example:** If the same participant above (with a relative \( \dot{V}_O₂ \) of 41.9 ml-kg\(^{-1}\)-min\(^{-1}\)) exercises, the intensity of the exercise and the fuel being utilized for energy production. RER increases during graded exercise in parallel with the increase in exercise intensity. It begins from a low of around 0.70–0.75 at rest; it increases to around 0.85–0.90 during moderate intensity exercise; then it peaks at around 1.10–1.20 during maximal intensity exercise. In fact, an RER in excess of 1.10 is one criterion to determine whether a person has reached a maximal oxygen consumption. Less importantly for this lab, but still important nutritionally, is the ability to use RER to determine the type of fuel being utilized. When RER = 0.70, the sole source of energy is fat (100 % of the energy is derived from fat). When RER = 1.00 or above, the sole source of energy is carbohydrate (100 % of the energy is derived from carbohydrate). This concept can be
Table 15.8: Total Kilocalories (kcal) Expended per Liter of Oxygen (kcal·L⁻¹ O₂) and Percent Contribution and Caloric Expenditure from Fat and Carbohydrate Based on Respiratory Exchange Ratio (RER)

<table>
<thead>
<tr>
<th>RER</th>
<th>Fat kcal</th>
<th>Fat %</th>
<th>Carbohydrate kcal</th>
<th>Carbohydrate %</th>
<th>Total kcal</th>
<th>Fat kcal</th>
<th>Fat %</th>
<th>Carbohydrate kcal</th>
<th>Carbohydrate %</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.71</td>
<td>4.69</td>
<td>99</td>
<td>4.6</td>
<td>1</td>
<td>0.7</td>
<td>0.86</td>
<td>4.88</td>
<td>48</td>
<td>2.3</td>
</tr>
<tr>
<td>0.72</td>
<td>4.71</td>
<td>95</td>
<td>4.5</td>
<td>5</td>
<td>0.2</td>
<td>0.87</td>
<td>4.89</td>
<td>44</td>
<td>2.2</td>
</tr>
<tr>
<td>0.73</td>
<td>4.72</td>
<td>92</td>
<td>4.3</td>
<td>8</td>
<td>0.4</td>
<td>0.88</td>
<td>4.90</td>
<td>41</td>
<td>2.0</td>
</tr>
<tr>
<td>0.74</td>
<td>4.73</td>
<td>88</td>
<td>4.2</td>
<td>12</td>
<td>0.6</td>
<td>0.89</td>
<td>4.91</td>
<td>37</td>
<td>1.8</td>
</tr>
<tr>
<td>0.75</td>
<td>4.74</td>
<td>85</td>
<td>4.0</td>
<td>16</td>
<td>0.7</td>
<td>0.90</td>
<td>4.93</td>
<td>34</td>
<td>1.7</td>
</tr>
<tr>
<td>0.76</td>
<td>4.75</td>
<td>82</td>
<td>3.9</td>
<td>18</td>
<td>0.9</td>
<td>0.91</td>
<td>4.94</td>
<td>31</td>
<td>1.5</td>
</tr>
<tr>
<td>0.77</td>
<td>4.77</td>
<td>75</td>
<td>3.7</td>
<td>22</td>
<td>1.0</td>
<td>0.92</td>
<td>4.95</td>
<td>27</td>
<td>1.3</td>
</tr>
<tr>
<td>0.78</td>
<td>4.78</td>
<td>75</td>
<td>3.6</td>
<td>25</td>
<td>1.2</td>
<td>0.93</td>
<td>4.96</td>
<td>24</td>
<td>1.2</td>
</tr>
<tr>
<td>0.79</td>
<td>4.79</td>
<td>71</td>
<td>3.4</td>
<td>29</td>
<td>1.4</td>
<td>0.94</td>
<td>4.98</td>
<td>20</td>
<td>1.0</td>
</tr>
<tr>
<td>0.80</td>
<td>4.80</td>
<td>68</td>
<td>3.3</td>
<td>32</td>
<td>1.5</td>
<td>0.95</td>
<td>4.99</td>
<td>17</td>
<td>0.8</td>
</tr>
<tr>
<td>0.81</td>
<td>4.82</td>
<td>65</td>
<td>3.1</td>
<td>35</td>
<td>1.7</td>
<td>0.96</td>
<td>5.00</td>
<td>14</td>
<td>0.7</td>
</tr>
<tr>
<td>0.82</td>
<td>4.83</td>
<td>61</td>
<td>3.0</td>
<td>39</td>
<td>1.9</td>
<td>0.97</td>
<td>5.01</td>
<td>10</td>
<td>0.5</td>
</tr>
<tr>
<td>0.83</td>
<td>4.84</td>
<td>58</td>
<td>2.8</td>
<td>42</td>
<td>2.0</td>
<td>0.98</td>
<td>5.03</td>
<td>7</td>
<td>0.3</td>
</tr>
<tr>
<td>0.84</td>
<td>4.85</td>
<td>54</td>
<td>2.6</td>
<td>46</td>
<td>2.2</td>
<td>0.99</td>
<td>5.04</td>
<td>3</td>
<td>0.2</td>
</tr>
<tr>
<td>0.85</td>
<td>4.87</td>
<td>51</td>
<td>2.5</td>
<td>49</td>
<td>2.4</td>
<td>1.00</td>
<td>5.05</td>
<td>0</td>
<td>0</td>
</tr>
</tbody>
</table>

Note: Total caloric expenditure per liter of oxygen (Total kcal) can be estimated by kcal = (1.23 · RER) + 0.82. The percent contribution from fat (Fat %) can be estimated by Fat % = (−340 · RER) + 340. The percent contribution from carbohydrate (Carbohydrate %) is the remainder from 100%.

Source: Data from Carpenter [1948].

explained by reviewing two summary reactions (Eq. 15.11a and 15.11b), one for the complete aerobic breakdown of 1 mole of fat (palmitic acid) and the other for the aerobic breakdown of 1 mole of carbohydrate (glucose). The value of the RER can be used to determine the fractional utilization of fat or carbohydrate, and the actual energy expended from fat or carbohydrate for any exercise intensity, as seen in Table 15.8. RER rises in direct relation to exercise intensity, so it should be clear from Table 15.8 that fat is the primary energy source for lower intensity exercise (when RER < 0.85) and that carbohydrate is the preferred source for higher intensity exercise (when RER > 0.85).

1 Palmitic acid (C₁₆H₃₂O₂) + 23 O₂ → 16 CO₂ + 16 H₂O

Where: CO₂/O₂ = 16/23 = 0.70 \quad \text{Eq. 15.11a}

1 Glucose (C₆H₁₂O₆) + 6 O₂ → 6 CO₂ + 6 H₂O

Where: CO₂/O₂ = 6/6 = 1.00 \quad \text{Eq. 15.11b}

Energy Expenditure

The final metabolic variable related to oxygen consumption to be calculated and discussed in this chapter is energy expenditure in kcal·min⁻¹. Energy expenditure can be estimated from oxygen consumption by the process of indirect calorimetry. The caloric equivalent of 1 liter of oxygen ranges from 4.67 to 5.05, but is assumed to be 5 kcal for simplicity. That is to say, 5 kcal of energy is expended for every 1 liter of O₂ consumed. So energy expenditure can be calculated by multiplying the VO₂ (L·min⁻¹) by the assumed caloric equivalent of 5.0 kcal·L⁻¹ (Eq. 15.12a). Although the metric unit for energy is the kilojoule (kJ), because kcal is still used so widely in the United States, it is used here. The conversion from kcal to kJ can be done simply by multiplying by 4.186 kJ·kcal⁻¹ if so desired, as seen in Equation 15.12b. Using the previously reported VO₂ of 3.35 L·min⁻¹, energy expenditure is estimated to be 16.8 kcal·min⁻¹ (Eq. 15.12c) or 70.3 kJ·min⁻¹ (Eq. 15.12d).

Energy (kcal·min⁻¹) = VO₂ (L·min⁻¹) 
  * 5.0 kcal·L⁻¹ \quad \text{Eq. 15.12a}

Energy (kJ·min⁻¹) = Energy (kcal·min⁻¹) 
  * 4.186 kJ·kcal⁻¹ \quad \text{Eq. 15.12b}

Energy (kcal·min⁻¹) = 3.35 L·min⁻¹ 
  * 5.0 kcal·L⁻¹ = 16.8 kcal·min⁻¹ \quad \text{Eq. 15.12c}

Energy (kJ·min⁻¹) = 16.8 kcal·min⁻¹ 
  * 4.186 kJ·kcal⁻¹ = 70.3 kJ·min⁻¹ \quad \text{Eq. 15.12d}

RESULTS AND DISCUSSION

The emphasis in this chapter is on the measurement of maximal oxygen consumption (VO₂max) as a measure of aerobic fitness. Because VO₂max depends on the body's maximal ability to deliver oxygen, it reflects the health and training status of the heart and lungs. And secondly, because it is also determined by the maximal ability to extract oxygen, it reflects the ability of the blood vessels to redistribute blood to the working muscle and the level of training of the skeletal muscle itself (i.e., capillary density, mitochondrial density, enzyme activity, etc.). In general, VO₂max is found to be (1) higher in men than in women,
Table 15.9 Aerobic Fitness Category for Men and Women for Maximal Oxygen Consumption

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Excellent</td>
<td>&gt; 92</td>
<td>&gt; 61</td>
<td>&gt; 55</td>
<td>&gt; 50</td>
<td>&gt; 53</td>
<td>&gt; 49</td>
<td>&gt; 45</td>
<td>&gt; 45</td>
</tr>
<tr>
<td>Very Poor</td>
<td>&lt; 33</td>
<td>&lt; 31</td>
<td>&lt; 29</td>
<td>&lt; 26</td>
<td>&lt; 28</td>
<td>&lt; 27</td>
<td>&lt; 24</td>
<td>&lt; 21</td>
</tr>
</tbody>
</table>

Source: Based on adaptation of data from Shwartz & Fleisch (1990).\(^{60}\)

(2) higher in younger adults than in older adults, (3) higher in aerobically trained persons than in anaerobically trained or in untrained persons, and (4) higher when tested using a mode of exercise that requires a larger muscle mass (e.g., cross-country skiing ergometer or treadmill) compared to a smaller muscle mass (e.g., cycle ergometer).

Fitness categories and comparative data for men and women over a wide range of age groups are provided in Table 15.9. It can be seen that relative VO\(_2\text{max}\) in men averages about 10 ml·kg\(^{-1}\)·min\(^{-1}\) higher than women across all age groups. This is partly due to gender differences in cardiorespiratory factors (e.g., heart size, maximal cardiac output, etc.) but is also due in large part to the greater percent body fat characteristic of women compared to men. The decrease in VO\(_2\text{max}\) with age apparent in Table 15.9 is possibly explained by a decrease in maximal heart rate due to changes in the autonomic nervous system and a decrease in maximal stroke volume due to reduced myocardial contractility and reduced vascular compliance, the combination of which results in a decrease in maximal cardiac output.\(^{56}\)

The data in Table 15.9 come from a study that compiled results from 62 different studies of healthy, untrained males and females ages 6–75 y from the United States, Canada, and Europe.\(^{60}\) They found that absolute VO\(_2\text{max}\) increased in male youths from about 1.0 L·min\(^{-1}\) at age 6 y to over 3.0 L·min\(^{-1}\) by age 18 y, then decreased to about 1.5 L·min\(^{-1}\) by age 75 y. A similar trend was observed in females whose absolute VO\(_2\text{max}\) was about 0.8 L·min\(^{-1}\) at age 6 y, peaked at about 2.2 L·min\(^{-1}\) at age 18 y, and decreased to about 1.0 L·min\(^{-1}\) by age 75 y. They further observed relative VO\(_2\text{max}\) differences with age and gender and found smaller gender differences and a considerably smaller increase from 6 y to 18 y when compared with absolute VO\(_2\text{max}\). Relative VO\(_2\text{max}\) decreased with age in males from a high of about 50 ml·kg\(^{-1}\)·min\(^{-1}\) during late adolescence (age 13–15 y) to about 25 ml·kg\(^{-1}\)·min\(^{-1}\) at age 75 y, or a rate of about 4 ml·kg\(^{-1}\)·min\(^{-1}\) per decade. Females demonstrated a high of about 40 ml·kg\(^{-1}\)·min\(^{-1}\) in late adolescence, which decreased to 17 ml·kg\(^{-1}\)·min\(^{-1}\) by age 75 y, at a rate similar to men.

Several investigators and reviewers support the use of VO\(_2\text{max}\) as the best single indicator of a person's capacity for maintaining endurance-type activity.\(^{44,54,56}\) A high relative VO\(_2\text{max}\) reflects the ability to sustain a high percentage of absolute VO\(_2\text{max}\) during aerobic activity. Relative VO\(_2\text{max}\) may also be used as a predictor of endurance running performance because of its inverse relationship with 1.5 mile running time (\(r = -0.74\)).\(^{40}\) Other investigators question the use of VO\(_2\text{max}\) alone as an indicator of success in aerobic performance. They encourage the use of factors such as running economy,\(^{20}\) the fractional utilization of VO\(_2\text{max},^{18}\) and metabolic or ventilatory thresholds,\(^{65}\) in addition to VO\(_2\text{max},^{18}\) to more accurately predict performance. For example, when aerobic performance is predicted with the addition of the fractional utilization of VO\(_2\text{max},^{18}\) the correlation with 1.5 mile run time is significantly improved from \(r = -0.74\) to \(r = -0.86\) compared to using VO\(_2\text{max}\) alone.\(^{40}\)

Aerobically trained athletes demonstrate very high VO\(_2\text{max}\) values as a result of years of aerobic training. Representative ranges of VO\(_2\text{max}\) values by sport are seen in Table 15.10. Sports characterized by continuous, long duration, aerobic activity such as Nordic (cross-country) skiing, distance running, rowing, and road cycling show the highest VO\(_2\text{max}\) values ranging in men from 60 to 94 ml·kg\(^{-1}\)·min\(^{-1}\) and in women from 47 to 75 ml·kg\(^{-1}\)·min\(^{-1}\).\(^{66}\) Athletes who compete in more discontinuous, anaerobic sports like basketball, football, and volleyball still have good aerobic endurance, but have considerably lower VO\(_2\text{max}\) values in the range of 40 to 60 ml·kg\(^{-1}\)·min\(^{-1}\).

Treadmill protocols typically elicit VO\(_2\text{max}\) values that range from 5% to 14% higher than cycle ergometry because of the greater amount of muscle mass involved. The larger muscle mass requires greater energy demand that subsequently requires increased oxygen consumption and aerobic metabolism. The greater VO\(_2\text{max}\) with treadmill running is likely to be more pronounced in those who are untrained or those who train by running. Trained cyclists however, because they spend so many hours training specifically on the bike, can elicit the same
or higher $\dot{V}O_2\text{max}$ on a cycle ergometer as on the treadmill. Arm ergometer protocols, which use considerably less muscle mass than leg ergometer or treadmill protocols, produce a $V\dot{O}_2\text{max}$ 20–30% lower when compared to the treadmill.\textsuperscript{56} This is probably also due in part to the fact that most persons do not regularly aerobically train or even use their arms to the same degree as their legs, further supporting the specificity of training concept.

**Summary**

Maximal oxygen consumption ($\dot{V}O_2\text{max}$) is an important physiological variable that can be directly measured in the exercise physiology laboratory. It is highly dependent on the ability of the heart and lungs to supply oxygen and on the ability of the skeletal muscles to extract oxygen. For this reason, it reflects a person’s overall aerobic or cardiorespiratory fitness very well. $V\dot{O}_2\text{max}$ also determines a person’s maximal aerobic power, which means that it contributes to sports and physical performances that rely predominantly on aerobic metabolism. The preferred method for determining $V\dot{O}_2\text{max}$ is to directly measure it by exercising to exhaustion as evidenced by specific physiological and psychological criteria. However, numerous field tests involving walking, jogging, running, cycling, and stepping are also available that indirectly estimate $V\dot{O}_2\text{max}$ through the use of submaximal exercise and the relationships observed between oxygen consumption, heart rate, running speed, cycle power level, and stepping rate and height. These indirect tests, because of the variability inherent in human physiology and performance, estimate $V\dot{O}_2\text{max}$ with an error of ± 10%. A comparison of the $V\dot{O}_2\text{max}$ values derived from the aerobic tests described in the previous chapters with directly measured $V\dot{O}_2\text{max}$ can be made.

**References**


