MAXIMAL OXYGEN CONSUMPTION

A test of aerobic fitness that truly qualifies as a laboratory test is the Maximal Oxygen Consumption (VO_2max) 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_2max 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_2max 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_2max, is inversely related to coronary heart disease and all-cause mortality.[6,28]

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.[44,54,64] 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_2max Test is also an important indicator of success for all-out events lasting between 20 min and 4 h.[53]

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.[11] 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.[31]

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.[42] So, if one participant completes several

exercise tests using different modes, the test that yields the highest $\dot{V}O_2$ value would be used as the true maximal oxygen consumption ($\dot{V}O_2$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 ($\dot{V}O_2$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 ($\dot{V}O_2$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 $\dot{V}O_2$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

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BOX 15.1   Accuracy of the $\dot{V}O_2$max Test

The accuracy of the Maximal Oxygen Consumption Test is maximized by achieving the traditional criteria of the max test, such as (1) the plateau of the oxygen consumption despite an increase of power level, (2) the attainment of respiratory exchange ratios > 1.0, (3) the plateau of heart rate, (4) high blood lactates, and (5) the exhaustion of the participant.

Validity

The validity of any exercise test is partly dependent upon the exercise modality and the specific fitness of the participant. Although not supported by all physiologists,[19,46] most investigators and reviewers[2,44,54,64] have supported the maximal oxygen consumption value as the best single physiological indicator of a person's capacity for endurance activities dependent upon the cardiorespiratory system. High maximal oxygen consumptions, when expressed relative to body mass ($ml \cdot kg^{-1} \cdot min^{-1}$), are associated with successful running performance in events lasting more than a couple minutes. For example, correlations of 0.90 and 0.91 have been reported between $\dot{V}O_2$max and 12 min distance.[17,27] However, a lower correlation of -0.74 was reported between $\dot{V}O_2$max and 1.5 mile time.[40]

Reliability

The test-retest reliability of maximal oxygen consumption tests is high—about 0.95[46,64] to 0.99.[11] The intraclass correlation coefficient is 0.93 and the day-to-day variability is < 5 % or ≈ 2 $ml \cdot kg^{-1} \cdot min^{-1}$.[50] The standard error *(SE)* of the $\dot{V}O_2$max Test may range from a low of about 2.5 %[64] to a high of about 5–6 %[37] of the mean score for an average person; it may extend up to about 8 % in aerobically trained males.[15] Thus, an individual would be expected to vary by about 2 to 4 $ml \cdot kg^{-1} \cdot min^{-1}$, even when tested weeks apart.[11,42,64] For example, if a person's maximal oxygen consumption is truly 40 $ml \cdot kg^{-1} \cdot min^{-1}$, then repeated tests with an *SE* of 5 % would be expected to vary between 38.0 and 42.0 $ml \cdot kg^{-1} \cdot min^{-1}$. The $\dot{V}O_2$max is highly consistent even over four months, having an average coefficient of variation of about 4.3 %.[68]

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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

Speed (Based on 1 mph = 1.609 km·h^{-1} = 26.8 m·min^{-1})

mph	km·h^{-1}	m·min^{-1}	mph	km·h^{-1}	m·min^{-1}
1.7	2.7	46	5.5	8.8	147
2.0	3.2	54	6.0	9.7	161
2.5	4.0	67	6.5	10.5	174
3.0	4.8	80	7.0	11.3	188
3.5	5.6	94	7.5	12.1	201
4.0	6.4	107	8.0	12.9	214
4.5	7.2	121	8.5	13.7	228
5.0	8.0	134	9.0	14.5	241

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

%	degrees	%	degrees
1%	0.6°	9%	5.1°
2%	1.2°	10%	5.7°
3%	1.8°	11%	6.3°
4%	2.3°	12%	6.8°
5%	2.9°	13%	7.4°
6%	3.4°	14%	8.0°
7%	4.0°	15%	8.5°
8%	4.6°	16%	9.1°

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 ($\approx$ 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 ($\dot{V}_E$) and the fractions of exhaled oxygen (F_EO_2) and carbon dioxide (F_ECO_2)—need to be continuously measured throughout the test in order to determine oxygen consumption and a variety of related metabolic variables (e.g., CO_2 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 ($\dot{V}_E$). 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 ($\dot{V}_I$). 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 O_2 and CO_2, 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_EO_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_ECO_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
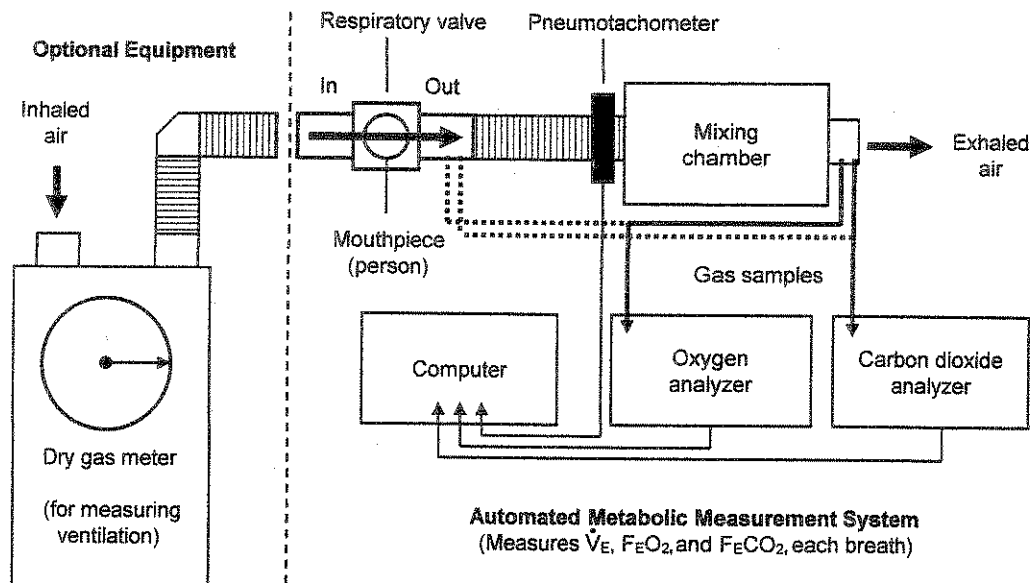
Figure 15.1 Schematic of the components of an automated (computerized) metabolic measurement system for measuring ventilation ($\dot{V}_E$) and the fractions of exhaled O_2 (F_EO_2) and CO_2 (F_ECO_2). In some cases, gas samples are drawn from the respiratory valve (instead of the mixing chamber) and $\dot{V}_E$ is measured with a turbine or spirometer (usually if nonautomated). Optionally, a dry gas meter can be used to measure inhaled (or exhaled) ventilation.
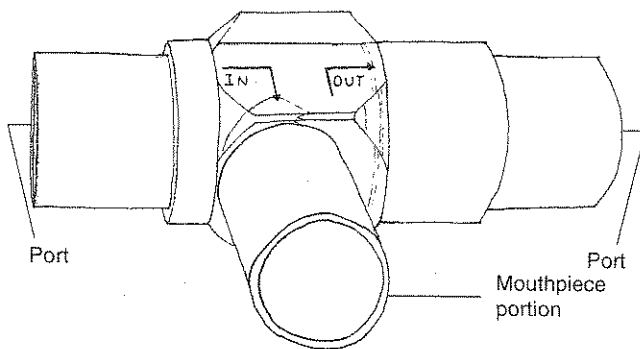
Figure 15.2 A two-way, non-rebreathing respiratory valve prevents air from exiting the same port that it entered.
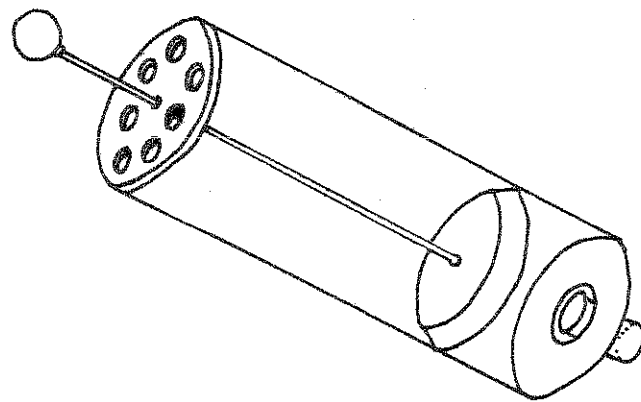
Figure 15.3 A 3 L syringe helps calibrate the ventilation volume measured by an air volume meter.

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_EO_2 and F_ECO_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_EO_2 and F_ECO_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 $\dot{V}O_2$max 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 O_2 and CO_2 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]

Table 15.2 Cycle Ergometer Protocols for Measuring $\dot{V}O_2$max

	Below average fitness	Average fitness	Above average fitness
Warm-up			
0:00–5:00	25 W	75 W	150 W
Exercise			
0:00–2:00	50 W	100 W	175 W
2:00–4:00	75 W	125 W	200 W
4:00–6:00	100 W	150 W	225 W
6:00–8:00	125 W	175 W	250 W
8:00–10:00	150 W	200 W	275 W
10:00–12:00	175 W	225 W	300 W
12:00–14:00	200 W	250 W	325 W
Recovery			
0:00–3:00	50–75 W	50–75 W	125–200 W

Cycling Protocols

Before the test, the estimated $\dot{V}O_2$max 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 protocol[39] 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 $\dot{V}O_2$max 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.[25] 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 predicting[1,5,38] and directly measuring maximal oxygen consumption.[46]

and supramaximal exercise relative to $\dot{V}O_2$max. The supramaximal portion contributes highly to the participant's exhaustion.

Several protocols may be used to elicit peak or maximal oxygen consumption.[2] Some of these are described in Chapter 19 on the ECG Test, while two protocols are presented, one for the cycle ergometer and one for the treadmill, in this chapter.

Although it is possible to reach nearly the maximal oxygen consumption level in 1 min when performing an all-out 90 s cycling task,[59] the test (excluding warm-up) is seldom less than 5 min and often no longer than 9 min. Occasionally, it is as long as 20 min for aerobically fit individuals starting at low stages, or if a longer time for monitoring the electrocardiogram is desired, or if mechanical efficiency is being measured simultaneously. Some investigators recommend a continuous protocol that brings participants to their limit of tolerance in about 10 min ± 2 min.[13]

Table 15.3	Estimation of Relative Oxygen Consumption (ml·kg^{-1}·min^{-1}) from Cycle Power (W)					
	$\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) Body Weight (kg)					
Cycle Power	50	60	70	80	90	100
50 W	18	16	15	14	13	12
75 W	23	21	19	17	16	15
100 W	29	25	22	21	19	18
125 W	34	30	26	24	22	21
150 W	39	34	30	27	25	23
175 W	45	39	34	31	28	26
200 W	50	43	38	34	31	29
225 W	56	48	42	37	34	31
250 W	61	52	46	41	37	34
275 W	66	57	49	44	40	37
300 W	72	61	53	48	43	39

Note: Estimated $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) is based on equation from American College of Sports Medicine (2000)[2] as follows: $\dot{V}O_2 = [(10.8 * \text{Power (W)}) / \text{Body weight (kg)} + 7]$.

Table 15.4	Bruce Treadmill Protocol with Estimated $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) Based on Speed and Grade			
Modified Bruce	Stage	Speed (mph)	Grade (%)	Est'd $\dot{V}O_2$
0:00–3:00	0	1.7	0	8.1
3:00–6:00	0	1.7	5	12.2
Standard Bruce	Stage	(mph)	Grade (%)	Est'd $\dot{V}O_2$
0:00–3:00	1	1.7	10	16.3
3:00–6:00	2	2.5	12	24.7
6:00–9:00	3	3.4	14	35.6
9:00–12:00	4	4.2	16	47.2
12:00–15:00	5	5.0	18	52.0
15:00–18:00	6	5.5	20	59.5
18:00–21:00	7	6.0	22	67.5
Recovery		(mph)	Grade (%)	Est'd $\dot{V}O_2$
0:00–3:00		2.5	0	9.7

Note: Estimated $\dot{V}O_2$ (ml·kg^{-1}·min^{-1}) is based on equations from American College of Sports Medicine (2000)[2] as follows: $\dot{V}O_2 = [(0.1 * \text{Speed (m·min}^{-1}))$ $+ (1.8 * \text{Speed} * \text{Grade (\%)} / 100) + 3.5]$ for walking; and $\dot{V}O_2 = [(0.2 * \text{Speed}$ $(\text{m·min}^{-1})) + (0.9 * \text{Speed} * \text{Grade (\%)} / 100) + 3.5]$ for running (5 mph and over).

The Bruce protocol (Table 15.4) consists of seven 3 min stages. Most participants should walk during the initial three stages in the first 9 min.[9] Although the initial stages are important for cardiovascular screening (e.g., ECG monitoring), they are sometimes deleted when the primary purpose is to measure maximal oxygen consumption; in these cases, the initial stage for $\dot{V}O_2$max testing is dependent upon the fitness level of the participant. Table 15.4 also lists the approximate oxygen costs for each completed stage of the Bruce protocol.[2] The oxygen cost of treadmill running is reduced if the participant relies on the handrails.[10] Therefore, tables and equations relating $\dot{V}O_2$ to exercise stages are not valid when the participant uses the handrails. While on the treadmill, the participant should look straight ahead to prevent possible nausea from viewing the moving belt. Both the speed and grade of the treadmill should be calibrated annually. Instructions for treadmill calibration are usually in the manufacturer's instruction manual or other sources.[39]

Criteria for Establishing Maximal Oxygen Consumption

Part of the protocol of the Maximal Oxygen Consumption Test is to establish whether the participant reached a maximal level of exertion. A number of criteria have been described that indicate a maximal test, including those of a *physiological* nature that are measured during or after the test and those of a *psychological* nature involving exertion and motivation.

It has been recommended that for the test to be considered maximal it should result in one or more of the following physiological observations: (1) a plateau in oxygen consumption with increasing workload,[4,33,34,52,53,64] (2) a respiratory exchange ratio (RER) greater than 1.05–1.15,[2,3,22,34,41,53,55] (3) a blood lactate greater than 8–10 mM·L^{-1},[2,23,41,53] and/or (4) a heart rate within 10–12 beats of age-predicted maximal heart rate (HRmax = 220 − age).[24,43,53,67] The observation of a plateau in oxygen con-

sumption (i.e., a $\dot{V}O_2$ below that predicted from the linear relationship observed at lower intensities) with an increase in workload is not without controversy. The concept has "historical roots" in the writings of Hill[33] and Taylor[64] and Åstrand[4] over the last 35–80 years. Oxygen consumption "traditionally" was described to increase linearly to a point where it would increase no further (i.e., plateau) despite a further increase in running speed or workload. The original criterion for the plateau, which is still frequently cited,[34,52,53] compared the results of two repeated tests both run at 7 mph, but with the second test run at a grade 2.5 % higher than the first. If the two oxygen consumptions differed by less than 150 ml·min^{-1} or 2.1 ml·kg^{-1}·min^{-1}, the test conditions were considered to yield a maximal oxygen consumption. If a larger difference was observed, the test was repeated one or more times with another 2.5 % increase in grade until the difference was less than the criterion.[64] This specific criterion, however, by itself has limited practical value. An alternative approach is to define the plateau as an increase in $\dot{V}O_2$ of less than half of the *expected* increase estimated from the treadmill running speed and grade[52] or cycle power. The major problem with applying any "plateau criterion" at all is that it is frequently *not observed* over the course of a graded exercise test to exhaustion. Studies have observed a plateau in $\dot{V}O_2$ in only 17 % (12 of 71 tests) of adult men,[21] 33 % (8 of 24 tests) of children,[56,57] and in general no more than about 50–60 % of graded exercise tests.[21,23,37,62] In fact, there are researchers who report a nonlinear *increase* in $\dot{V}O_2$ (i.e., the opposite of a plateau) during graded exercise at high power

levels,[30,69,70] possibly due to increased lactate and hydrogen ion concentration, increased muscle temperature, and/or recruitment of less efficient fast-twitch muscle fibers.[69] In summary, the *presence* of a plateau (however defined) in $\dot{V}O_2$ 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 $\dot{V}O_2$ 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,[22] 1.10,[34,41] or 1.15.[2,3,53,55] A high RER (≥ 1.00) indicates an increase in carbon dioxide production proportionately greater than the related increase in oxygen consumption. The accelerated CO_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 $\geq$ 1.15). Another criterion is a venous *blood lactate* concentration in excess of 8 mM·L^{-1} [2,23,53] or 10 mM·L^{-1}.[41] These values are 8–10 times the typical blood lactate concentration at rest (1 mM·L^{-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 $\dot{V}O_2$ is being directly measured, the participant reaches a *previously measured* maximal heart rate, it can be assumed that the $\dot{V}O_2$ 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 HRmax, but other sources consider an exercise heart rate within 12 bpm[24] or 10 bpm[43,53,67] of predicted HRmax 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,[7]

Table 15.5 Borg Rating of Perceived Exertion (RPE) Scale

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

Sources: From Borg (1970)[7] and Borg (1982).[8]

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.[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,[2] and was renamed the Borg 10-category ratio (CR-10) RPE scale.[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.[8,62] The choice of which scale to use is up to the tester. An RPE > 17[2] or an RPE of 19 or 20[41] have been recommended as indicating a maximal effort.

Procedures for the Maximal Oxygen Consumption Test

The initial steps for the $\dot{V}O_2$max 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.

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 $\dot{V}O_2$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_EO_2, F_ECO_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.
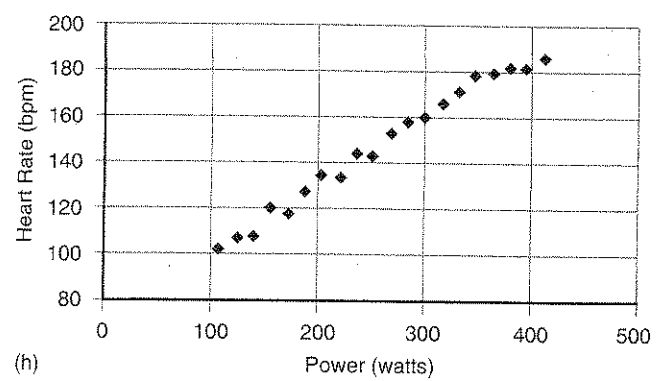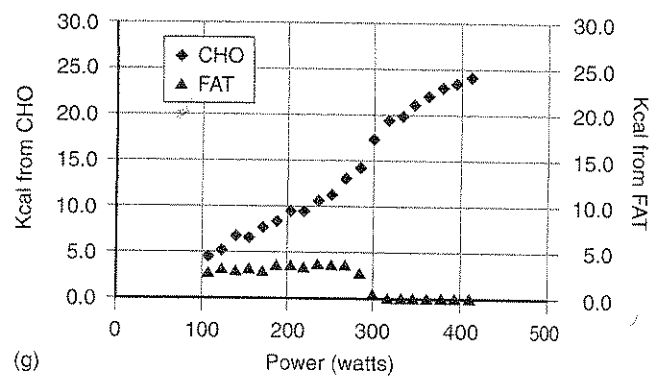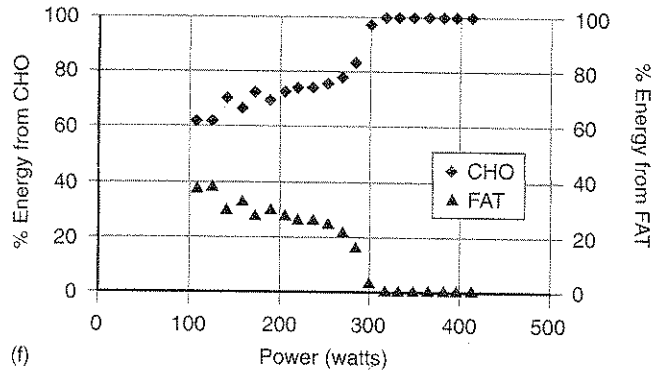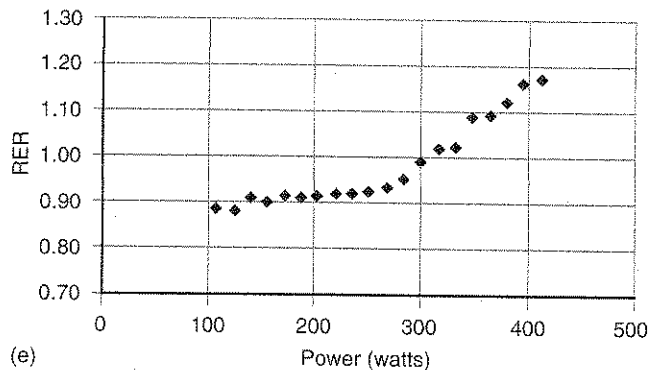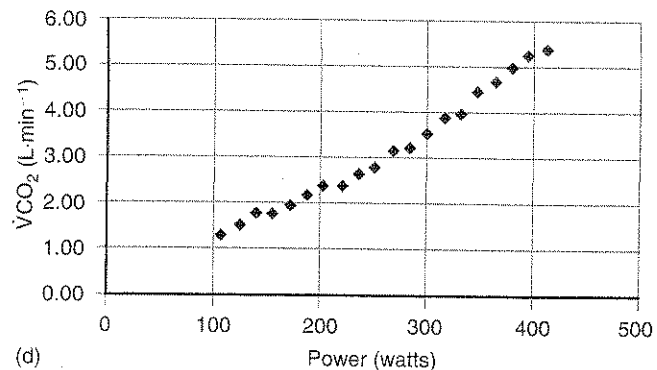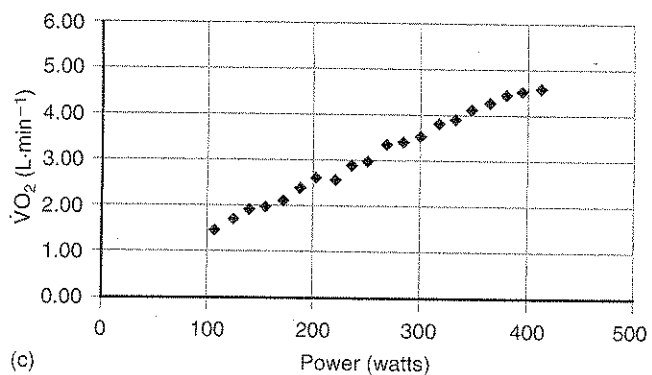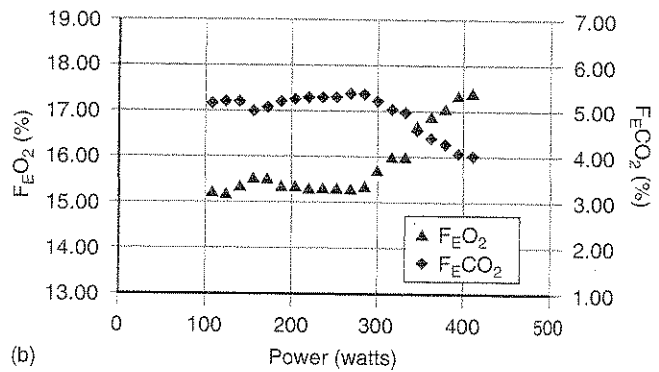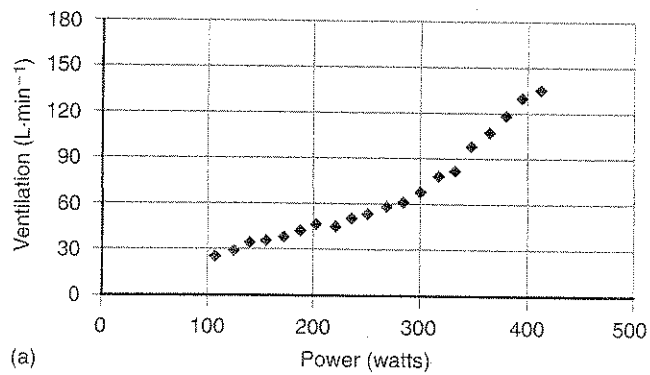
Figure 15.4. Sample data from graded exercise test showing: (a) ventilation, (b) F_EO_2 and F_ECO_2, (c) oxygen consumption, (d) CO_2 production, (e) respiratory exchange ratio, (f) % energy from carbohydrate and fat, (g) energy expenditure from carbohydrate and fat, and (h) heart rate.

However, an important concept in this chapter is how the raw data ($\dot{V}_E$, 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 ($\dot{V}_E$), 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 $\dot{V}_E$ 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 ATPS, 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 ATPS 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 $\dot{V}O_2$max values recorded under any ambient conditions, regardless of ambient temperature or barometric pressure, to be expressed in

Temperature		P_{H_2O}	Temperature		P_{H_2O}
°C	K	mm Hg	°C	K	mm Hg
20	293	18	26	299	25
21	294	19	27	300	27
22	295	20	28	301	28
23	296	21	29	302	30
24	297	22	30	303	32
25	298	24	37	310	47

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 $\dot{V}_E$ from ATPS 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.

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

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: $T_A = 24°C$; $P_B = 756$ mm Hg; and $P_{H_2O} = 22$ 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 ($\dot{V}_{E\ ATPS}$) 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 $\dot{V}_{E\ STPD} = \mathbf{88.8}$ L·min^{-1} (Eq. 15.2b).

$$\text{STPD CF} = \frac{[0\ °C + 273\ K]}{[24\ °C + 273\ K]}$$
$$* \frac{[\mathbf{756\ mm\ Hg} - 22\ mm\ Hg]}{[760\ mm\ Hg]} = \mathbf{0.888} \qquad \text{Eq. 15.2a}$$

Barometric Pressure (mm Hg)	STPD Correction Factors Ambient Temperature (°C)								
	20	21	22	23	24	25	26	27	28
740	0.885	0.881	0.877	0.873	0.868	0.863	0.859	0.854	0.850
742	0.888	0.883	0.879	0.875	0.871	0.865	0.861	0.856	0.852
744	0.890	0.886	0.882	0.877	0.873	0.868	0.864	0.859	0.854
746	0.893	0.888	0.884	0.880	0.876	0.870	0.866	0.861	0.857
748	0.895	0.891	0.886	0.882	0.878	0.873	0.869	0.863	0.859
750	0.897	0.893	0.889	0.885	0.880	0.875	0.871	0.866	0.862
752	0.900	0.896	0.891	0.887	0.883	0.878	0.873	0.868	0.864
754	0.902	0.898	0.894	0.890	0.885	0.880	0.876	0.870	0.866
756	0.905	0.900	0.896	0.892	0.888	0.882	0.878	0.873	0.869
758	0.907	0.903	0.899	0.894	0.890	0.885	0.881	0.875	0.871
760	0.910	0.905	0.901	0.897	0.893	0.887	0.883	0.878	0.874
762	0.912	0.908	0.904	0.899	0.895	0.890	0.885	0.880	0.876
764	0.915	0.910	0.906	0.902	0.897	0.892	0.888	0.882	0.878

Note: STPD CF = [(273 K) / (T_A + 273 K)] * [(P_B – P_{H_2O} at T_A) / (760 mm Hg)]; T_A = Ambient temperature; P_B = Barometric pressure; P_{H_2O} = Vapor pressure of water at ambient temperature.

$$\dot{V}_{E\,STPD}\ (L\cdot min^{-1}) = \dot{V}_{E\,ATPS}\ (L\cdot min^{-1}) * STPD\ CF$$
$$= 100 * 0.888 = 88.8\ L\cdot min^{-1} \qquad \text{Eq. 15.2b}$$

Oxygen Consumption

Three specific variables—pulmonary ventilation expressed in STPD conditions ($\dot{V}_{E\,STPD}$), and the fractions (or percentages) of exhaled or expired oxygen (F_EO_2) and carbon dioxide (F_ECO_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 ($\dot{V}O_2$), is literally the difference between the volume of oxygen being inhaled into the body ($\dot{V}_IO_2$) and the volume being exhaled from the body ($\dot{V}_EO_2$). 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 gasses. Given Equations 15.3c and 15.3d, substitution into Equation 15.3b yields Equation 15.3e.

Given: $\dot{V}O_2 = [\dot{V}O_2\ Inspired] - [\dot{V}O_2\ Expired]$ Eq. 15.3a

Given: $\dot{V}O_2 = [\dot{V}_IO_2] - [\dot{V}_EO_2]$ Eq. 15.3b

  Where: $\dot{V}_IO_2$: Volume of inspired O_2

  Where: $\dot{V}_EO_2$: Volume of expired O_2

Given: $\dot{V}_IO_2 = \dot{V}_I * F_IO_2$ Eq. 15.3c

  Where: $\dot{V}_I$: Volume of inspired air

  Where: F_IO_2: Fraction of inspired O_2

Given: $\dot{V}_EO_2 = \dot{V}_E * F_EO_2$ Eq. 15.3d

  Where: $\dot{V}_E$: Volume of expired air

  Where: F_EO_2: Fraction of expired O_2

Substitution yields: $\dot{V}O_2 = [\dot{V}_I * F_IO_2] - [\dot{V}_E * F_EO_2]$ 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 ($\dot{V}_I$) 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 ($\dot{V}_I N_2$) 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 $\dot{V}_I$ (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 ($\dot{V}_I$).

Assume: $\dot{V}_I N_2 = \dot{V}_E N_2$ Eq. 15.4a

  Where: $\dot{V}_I N_2$: Volume of inspired N_2

  Where: $F_I N_2$: Fraction of inspired N_2

Given: $\dot{V}_I N_2 = \dot{V}_I * F_I N_2$ Eq. 15.4b

Given: $\dot{V}_E N_2 = \dot{V}_E * V_E N_2$ 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: $\dot{V}_I * F_I N_2 = \dot{V}_E * F_E N_2$ Eq. 15.4d

Transposition yields: $\dot{V}_I = (\dot{V}_E * F_E N_2) / F_I N_2$ Eq. 15.4e

The final steps involved in deriving the desired mathematical equation for calculating $\dot{V}O_2$ involve substituting Equation 15.4e into Equation 15.3e to yield Equation 15.5a. Then one final step, substituting the assumed values of F_IN_2 and F_IO_2 (Eq. 15.5b), yields the desired equation (Eq. 15.5c). Typically the calculation of F_EN_2 (Eq. 15.5d) is done separately, but can also be substituted into Equation 15.5c if desired, resulting in one combined equation.

Substitution yields: $\dot{V}O_2 = [(\dot{V}_E * F_EN_2 / F_IN_2) * F_IO_2]$
$\qquad - [\dot{V}_E * F_EO_2]$
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ Eq. 15.5a

Given: $F_IN_2 = 0.7903$, and $F_IO_2 = 0.2093$ $\qquad$ Eq. 15.5b

Substitution yields: $\dot{V}O_2 = [(\dot{V}_{E\,STPD} * F_EN_2) * 0.2648]$
$\qquad - [\dot{V}_{E\,STPD} * F_EO_2]$
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ Eq. 15.5c

$\qquad$ *Where:* $F_EN_2 = 1.00 - (F_EO_2 + F_ECO_2)$ $\qquad$ Eq. 15.5d

Example: A person with a $\dot{V}_{E\,STPD} = 100\ L \cdot min^{-1}$, $F_EO_2 = 0.1750$ (17.5 %), $F_ECO_2 = 0.0375$ (3.75 %), and therefore $F_EN_2 = 0.7875$ (78.75 %), would have an absolute $\dot{V}O_2$ of 3.35 $L \cdot min^{-1}$, as seen in Equation 15.6.

$\dot{V}O_2 = [\mathbf{100 * 0.7875} * 0.2648] - [\mathbf{100 * 0.1750}]$
$\qquad = 20.85 - 17.50 = 3.35\ L \cdot min^{-1}$ $\qquad$ Eq. 15.6

Relative Oxygen Consumption

The oxygen uptake calculated in Equation 15.6 is considered an *absolute oxygen uptake* (expressed in $L \cdot min^{-1}$). This value is important because it is used to calculate respiratory exchange ratio and energy expenditure. However, when using $\dot{V}O_2max$ 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 $\dot{V}O_2$ from liters to milliliters by multiplying by 1000 ($ml \cdot L^{-1}$), then dividing by body weight (kg), as seen in Equation 15.7a.

Example: If the same participant above (with an absolute $\dot{V}O_2$ of 3.35 $L \cdot min^{-1}$) weighs 80 kg, the relative $\dot{V}O_2$ would be 41.9 $ml \cdot kg^{-1} \cdot min^{-1}$ (Eq. 15.7b).

Relative $\dot{V}O_2$ ($ml \cdot kg^{-1} \cdot min^{-1}$)
$\quad$ = Absolute $\dot{V}O_2$ ($L \cdot min^{-1}$)
$\quad$ * 1000 / Body weight (kg) $\qquad$ Eq. 15.7a

Relative $\dot{V}O_2 = \mathbf{3.35}\ L \cdot min^{-1} * 1000 / \mathbf{80}$ kg
$\quad = \mathbf{41.9}\ ml \cdot kg^{-1} \cdot min^{-1}$ $\qquad$ Eq. 15.7b

Carbon Dioxide Production

With increasing exercise intensity, there is an increase not only in $\dot{V}O_2$, but also in carbon dioxide production ($\dot{V}CO_2$) as a by-product of elevated aerobic metabolism. The measurement of $\dot{V}CO_2$ is important because it allows for the subsequent calculation of the respiratory exchange ratio

(RER). $\dot{V}CO_2$ is the difference between the volume of CO_2 exhaled from the lungs and the volume of CO_2 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 CO_2 inhaled into the lungs is negligible (since $F_ICO_2 = 0.0003$), the equation reduces to Equation 15.8c. And finally, because the volume of exhaled CO_2 is the product of the exhaled ventilation and the fraction of CO_2 (Eq. 15.8d), this may be substituted to yield the equation used to mathematically calculate $\dot{V}CO_2$ (Eq. 15.8e).

Given: $\dot{V}CO_2 = [\dot{V}CO_2\ Expired]$
$\qquad - [\dot{V}CO_2\ Inspired]$
$\qquad\qquad\qquad\qquad\qquad\qquad\qquad$ Eq. 15.8a

Given: $\dot{V}CO_2 = [\dot{V}_ECO_2] - [\dot{V}_ICO_2]$ $\qquad$ Eq. 15.8b

$\qquad$ *Where:* $\dot{V}_ECO_2$: Volume of expired CO_2

$\qquad$ *Where:* $\dot{V}_ICO_2$: Volume of inspired CO_2

$\qquad$ *Assume:* $\dot{V}_ICO_2$ is negligible ($F_ICO_2 = 0.0003$)

Given: $\dot{V}CO_2 = V_ECO_2$ $\qquad$ Eq. 15.8c

Given: $\dot{V}_ECO_2 = \dot{V}_E * F_ECO_2$ $\qquad$ Eq. 15.8d

Substitution yields: $\dot{V}CO_2 = \dot{V}_{E\,STPD} * F_ECO_2$ $\quad$ Eq. 15.8e

Example: A person with a $\dot{V}_{E\,STPD} = 100\ L \cdot min^{-1}$ and $F_ECO_2 = 0.0375$ (3.75 %), would have a $\dot{V}CO_2$ of 3.75 $L \cdot min^{-1}$, as seen in Equation 15.9.

$\dot{V}CO_2 = [\mathbf{100 * 0.0375}] = \mathbf{3.75}\ L \cdot min^{-1}$ $\qquad$ Eq. 15.9

Respiratory Exchange Ratio

RER, the ratio of carbon dioxide production to oxygen consumption, is calculated by dividing $\dot{V}CO_2$ by $\dot{V}O_2$ (Eq. 15.10a). Based on the previous examples, if $\dot{V}CO_2 = 3.75\ L \cdot min^{-1}$ and $\dot{V}O_2 = 3.35\ L \cdot min^{-1}$, then RER would be calculated as 1.12 (Eq. 15.10b).

RER $= \dot{V}CO_2$ ($L \cdot min^{-1}$) / $\dot{V}O_2$ ($L \cdot min^{-1}$) $\qquad$ Eq. 15.10a

RER $= \mathbf{3.75}\ L \cdot min^{-1} / \mathbf{3.35}\ L \cdot min^{-1} = \mathbf{1.12}$ $\qquad$ Eq. 15.10b
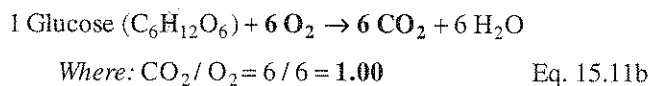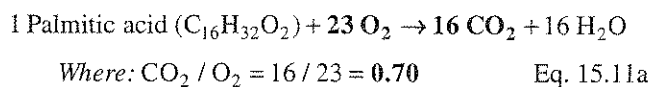
RER reflects two important characteristics with regard to exercise, the *intensity* of the exercise and the *fuel being utilized* for energy production. RER increases during graded exercise in parallel with the increase in exercise intensity. It begins from a low of around 0.70–0.75 at rest; it increases 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 ($kcal \cdot L^{-1} O_2$) and Percent Contribution and Caloric Expenditure from Fat and Carbohydrate Based on Respiratory Exchange Ratio (RER)

Total		Fat		Carbohydrate		Total		Fat		Carbohydrate	
RER	kcal	%	kcal	%	kcal	RER	kcal	%	kcal	%	kcal
0.71	4.69	99	4.6	1	0.1	0.86	4.88	48	2.3	52	2.6
0.72	4.71	95	4.5	5	0.2	0.87	4.89	44	2.2	56	2.7
0.73	4.72	92	4.3	8	0.4	0.88	4.90	41	2.0	59	2.9
0.74	4.73	88	4.2	12	0.5	0.89	4.91	37	1.8	63	3.1
0.75	4.74	85	4.0	15	0.7	0.90	4.93	34	1.7	66	3.3
0.76	4.75	82	3.9	18	0.9	0.91	4.94	31	1.5	69	3.4
0.77	4.77	78	3.7	22	1.0	0.92	4.95	27	1.3	73	3.6
0.78	4.78	75	3.6	25	1.2	0.93	4.96	24	1.2	76	3.8
0.79	4.79	71	3.4	29	1.4	0.94	4.98	20	1.0	80	4.0
0.80	4.80	68	3.3	32	1.5	0.95	4.99	17	0.8	83	4.1
0.81	4.82	65	3.1	35	1.7	0.96	5.00	14	0.7	86	4.3
0.82	4.83	61	3.0	39	1.9	0.97	5.01	10	0.5	90	4.5
0.83	4.84	58	2.8	42	2.0	0.98	5.03	7	0.3	93	4.7
0.84	4.85	54	2.6	46	2.2	0.99	5.04	3	0.2	97	4.9
0.85	4.87	51	2.5	49	2.4	1.00	5.05	0	0.0	100	5.1

Note: Total caloric expenditure per liter of oxygen (Total kcal) can be estimated by kcal = (1.23 * RER) + 3.82. 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).[14]

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 ($C_{16}H_{32}O_2$) + 23 O_2 → 16 CO_2 + 16 H_2O

Where: $CO_2 / O_2 = 16 / 23 = 0.70$ Eq. 15.11a

1 Glucose ($C_6H_{12}O_6$) + 6 O_2 → 6 CO_2 + 6 H_2O

Where: $CO_2 / O_2 = 6 / 6 = 1.00$ 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 $kcal \cdot min^{-1}$. 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,[14] but is assumed to be 5 kcal for simplicity. That is to say, 5 kcal of energy is expended for every 1 liter of O_2 consumed. So energy expenditure can be calculated by multiplying the $\dot{V}O_2$ ($L \cdot min^{-1}$) by the assumed caloric equivalent of 5.0 $kcal \cdot L^{-1}$ (Eq. 15.12a). Although the metric unit for energy is the kilojoule (kJ), be-

cause 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 $kJ \cdot kcal^{-1}$ if so desired, as seen in Equation 15.12b. Using the previously reported $\dot{V}O_2$ of 3.35 $L \cdot min^{-1}$, energy expenditure is estimated to be 16.8 $kcal \cdot min^{-1}$ (Eq. 15.12c) or 70.3 $kJ \cdot min^{-1}$ (Eq. 15.12d).

Energy ($kcal \cdot min^{-1}$) = $\dot{V}O_2$ ($L \cdot min^{-1}$)
   * 5.0 $kcal \cdot L^{-1}$ Eq. 15.12a

Energy ($kJ \cdot min^{-1}$) = Energy ($kcal \cdot min^{-1}$)
   * 4.186 $kJ \cdot kcal^{-1}$ Eq. 15.12b

Energy ($kcal \cdot min^{-1}$) = **3.35** $L \cdot min^{-1}$
   * 5.0 $kcal \cdot L^{-1}$ = **16.8** $kcal \cdot min^{-1}$ Eq. 15.12c

Energy ($kJ \cdot min^{-1}$) = **16.8** $kcal \cdot min^{-1}$
   * 4.186 $kJ \cdot kcal^{-1}$ = **70.3** $kJ \cdot min^{-1}$ Eq. 15.12d

RESULTS AND DISCUSSION

The emphasis in this chapter is on the measurement of maximal oxygen consumption ($\dot{V}O_2 max$) as a measure of aerobic fitness. Because $\dot{V}O_2 max$ 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, $\dot{V}O_2 max$ 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

| | Maximal Oxygen Consumption $(ml \cdot kg^{-1} \cdot min^{-1})$ | | | | | | | |
| | Men | | | | Women | | | |
Category	< 20 y	20–29 y	30–39 y	40–49 y	< 20 y	20–29 y	30–39 y	40–49 y
Excellent	> 62	> 61	> 55	> 50	> 53	> 49	> 45	> 39
Very Good	57–62	56–61	51–55	46–50	48–53	45–49	41–45	36–39
Good	51–56	50–55	46–50	41–45	43–47	41–44	36–40	32–35
Average	46–50	44–49	39–45	36–40	38–42	36–40	32–35	28–31
Fair	39–45	37–43	34–38	31–35	33–37	32–35	28–31	25–27
Poor	33–38	31–36	29–33	26–30	28–32	27–31	24–27	21–24
Very Poor	< 33	< 31	< 29	< 26	< 28	< 27	< 24	< 21

Source: Based on adaptation of data from Shvartz & Reibold (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 $\dot{V}O_2$max in men averages about 10 ml·kg·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 $\dot{V}O_2$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.[66] 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* $\dot{V}O_2$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 $\dot{V}O_2$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* $\dot{V}O_2$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 $\dot{V}O_2$max. Relative $\dot{V}O_2$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 $\dot{V}O_2$max as the best single indicator of a person's capacity for maintaining endurance-type activity.[44,54,64] A high relative $\dot{V}O_2$max reflects the ability to sustain a high percentage of absolute $\dot{V}O_2$max during aerobic activity. Relative $\dot{V}O_2$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 $\dot{V}O_2$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 $\dot{V}O_2$max,[18] and metabolic or ventilatory thresholds,[65] in addition to $\dot{V}O_2$max, to more accurately predict performance. For example, when aerobic performance is predicted with the addition of the fractional utilization of $\dot{V}O_2$max, the correlation with 1.5 mile run time is significantly improved from $r = -0.74$ to $r = -0.86$ compared to using $\dot{V}O_2$max alone.[40]

Aerobically trained athletes demonstrate very high $\dot{V}O_2$max values as a result of years of aerobic training. Representative ranges of $\dot{V}O_2$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 $\dot{V}O_2$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 $\dot{V}O_2$max values in the range of 40 to 60 ml·kg^{-1}·min^{-1}.

Treadmill protocols typically elicit $\dot{V}O_2$max values that range from 5 % to 14 % higher than cycle ergometry [22,32,35] 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 $\dot{V}O_2$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

Table 15.10 Maximal Oxygen Consumption Values by Sport

Sport	Age (y)	VO₂max (ml·kg⁻¹·min⁻¹) Men	Women
Skiing, Nordic	20–28	65–94	60–75
Running	18–39	60–85	50–75
Rowing	20–35	60–72	58–65
Cycling	18–26	62–74	47–57
Speed skating	18–24	56–73	44–55
Swimming	10–25	50–70	40–60
Canoeing	22–28	55–67	48–52
Soccer	22–28	54–64	50–60
Ice hockey	10–30	50–63	–
Wrestling	20–30	52–65	–
Basketball	18–30	40–60	43–60
Football	20–36	42–60	–
Volleyball	18–22	–	40–56
Gymnastics	18–22	52–58	36–50

Source: Data from Wilmore & Costill (2004).[67]

The header uses $\dot{V}O_2max$ (ml·kg⁻¹·min⁻¹).

or higher $\dot{V}O_2$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 $\dot{V}O_2$max 20–30 % lower when compared to the treadmill.[26] 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 ($\dot{V}O_2$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. $\dot{V}O_2$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 $\dot{V}O_2$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 $\dot{V}O_2$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 $\dot{V}O_2$max with an error of ± 10 %. A comparison of the $\dot{V}O_2$max values derived from the aerobic tests described in the previous chapters with directly measured $\dot{V}O_2$max can be made.

BOX 15.3 Chapter Preview/Review

What tissues (e.g., heart) and physiological variables (e.g., cardiac output) determine VO₂max?

What is the difference between "maximal" and "peak" oxygen consumption?

What are the criteria used to determine if an exercise test truly elicited a maximal physiological effort?

What is rate of perceived exertion (RPE)?

What is meant by STPD?

What is the difference between "absolute" and "relative" oxygen consumption?

How is the respiratory exchange ratio (RER) determined?

What does RER mean in terms of exercise intensity and fuel utilization?

How is energy expenditure determined from oxygen uptake?

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