

Assessment of Functional Capacity in Clinical and Research Applications

An Advisory From the Committee on Exercise, Rehabilitation, and Prevention, Council on Clinical Cardiology, American Heart Association

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A fundamental requirement for many of the activities of daily living is the ability to perform predominantly aerobic, ie, oxygen-using, work. Such activities require the integrated efforts of the heart, lungs, and circulation to deliver oxygen to the metabolically active muscle mass. Thus, the assessment of functional or aerobic exercise time or peak oxygen consumption provides important diagnostic and prognostic information in a wide variety of clinical settings. Furthermore, numerous clinical trials, especially those in patients with heart failure, have used aerobic exercise time or peak oxygen consumption as a primary or secondary end point. This brief advisory will highlight the major clinical and research applications of functional capacity assessment. For a comprehensive review of exercise testing, the reader is referred to the American College of Cardiology/American Heart Association Guidelines for Exercise Testing.¹

Physiology and Terminology

The maximal capacity of an individual to perform aerobic work is defined by the maximal oxygen consumption ($\dot{V}O_{2\max}$), the product of cardiac output (CO) and arteriovenous oxygen (AV O_2) difference at exhaustion. Although $\dot{V}O_{2\max}$ is measured in liters per minute, it is usually expressed per kilogram of body weight to facilitate intersubject comparisons. Functional capacity, particularly when estimated rather than measured directly, is often expressed in metabolic equivalents (METs); 1 MET represents resting energy expenditure and approximates $3.5 \text{ mL } O_2 \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$. Because $\dot{V}O_{2\max}$ is typically achieved by exercise that involves only about half of the total body musculature, it is generally believed that $\dot{V}O_{2\max}$ is limited by maximal CO rather than peripheral factors.²

$\dot{V}O_{2\max}$ is affected by age, sex, conditioning status, and the presence of diseases or medications that influence its components. $\dot{V}O_{2\max}$ in a young world-class male endurance athlete can exceed $80 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$, whereas a value of $15 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$ is typical for a sedentary but healthy

80-year-old woman. Aerobic capacity declines 8% to 10% per decade in nonathletic subjects,³ mediated largely by decreases in maximal heart rate and AV O_2 difference. Earlier studies suggested that the age-associated decline in $\dot{V}O_{2\max}$ may be attenuated to $\approx 5\%$ per decade in endurance-trained subjects who continue to exercise vigorously. However, recent longitudinal observations with >20 years of follow-up have demonstrated declines of 10% to 15% per decade in such individuals,⁴ mediated in part by a reduction in training intensity. At any age, $\dot{V}O_{2\max}$ in men is 10% to 20% greater than in women, in part because of a higher hemoglobin concentration, a larger proportion of muscle mass, and a greater stroke volume in men. These age and sex differences in $\dot{V}O_{2\max}$ must be considered in interpretations of functional capacity in individuals. Endurance training augments $\dot{V}O_{2\max}$ by 10% to 30% primarily by increasing maximal stroke volume and the AV O_2 difference.⁵ True $\dot{V}O_{2\max}$ is usually defined by a leveling off of $\dot{V}O_2$ between the final 2 exercise work rates and requires that maximal effort be achieved and sustained for ≥ 1 minute. A more realistic goal of testing in most populations is simply the attainment of "peak" $\dot{V}O_2$ rather than $\dot{V}O_{2\max}$.

Because most daily activities do not require maximal effort, a widely used submaximal index of aerobic capacity is the lactate, anaerobic, or ventilatory threshold (VT), defined by the exercise level at which ventilation begins to increase exponentially for a given increment in $\dot{V}O_2$. This increase in ventilation is necessitated to eliminate the excess CO_2 produced in response to a sustained rise in blood lactate. Although the VT usually occurs at 47% to 64% of $\dot{V}O_{2\max}$ in healthy untrained subjects,⁶ it generally occurs at a higher percentage of $\dot{V}O_{2\max}$ in endurance-trained individuals.⁷ Several methods have been proposed for determining VT; however, no universal agreement exists regarding which is best. The 3 most common definitions of VT are these: (1) the point at which a systematic increase in the ventilatory equivalent for oxygen ($\dot{V}E/\dot{V}O_2$) occurs without an increase in

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the ventilatory equivalent for carbon dioxide (\dot{V}_E/\dot{V}_{CO_2}); (2) the point at which a systematic rise in end-tidal oxygen pressure ($P_{ET}O_2$) occurs without a decrease in the end-tidal carbon dioxide pressure ($P_{ET}CO_2$); and (3) the departure of \dot{V}_{CO_2} from a line of identity drawn through a plot of \dot{V}_{CO_2} versus \dot{V}_{O_2} , often called the V-slope method.⁸ In a study by Shimizu et al,⁹ the VTs calculated by these 3 methods were 68%, 61%, and 65% of $\dot{V}_{O_2}max$, respectively. The confidence in determining the VT may be increased by having 2 or 3 experienced observers independently calculate this point. When 3 observers used the ventilatory equivalent method, 2 chose the same minute of exercise for VT in 100% of tests, and all 3 agreed in 71%.¹⁰

Exercise Mode and Protocol Selection

Assessment of functional capacity is typically performed on a motorized treadmill or a stationary cycle ergometer. Treadmill exercise is generally the preferred modality in the United States because most Americans do not regularly ride bicycles. Thus, untrained subjects will usually terminate cycle exercise because of quadriceps fatigue at a work rate 10% to 20% below their treadmill $\dot{V}_{O_2}max$.¹¹ Several studies, however, have demonstrated a consistent relationship between aerobic capacity on a treadmill and a cycle ergometer. To define this relationship, Foster et al¹² suggested the following formula: treadmill METs = 0.98(cycle ergometer METs) + 1. In addition, cycle ergometry requires subject cooperation in maintaining pedal speed at the desired level, usually about 60 rpm. Nevertheless, cycle ergometry may be preferred in subjects with gait or balance instability or when simultaneous cardiac imaging is planned. Although arm ergometry may be used to assess the aerobic capacity of wheelchair athletes, ambulatory persons cannot usually achieve high work rates because of the smaller muscle mass used compared with leg exercise.¹³

Functional capacity can be measured directly by determining $\dot{V}_{O_2}max$ or estimated from the highest treadmill or cycle work rate achieved. Because of the additional equipment and expertise required to perform respiratory gas exchange measurements, most exercise testing facilities, especially those outside the hospital setting, do not perform them. If the primary purpose of testing is to rule out significant coronary artery disease (CAD) by electrocardiography (ECG) or to provide a general assessment of fitness, respiratory gases need not be monitored. In these settings, $\dot{V}_{O_2}max$ can be estimated from published nomograms. It must be recognized, however, that there may be a sizeable discrepancy between estimated and measured $\dot{V}_{O_2}max$ because of the use of handrail support, differences in gait, different degrees of familiarity with treadmill exercise, and differences between the populations being tested and that from which the formula for estimating $\dot{V}_{O_2}max$ was derived.¹⁴ For these reasons, when an accurate and reproducible objective assessment of aerobic capacity is needed, $\dot{V}_{O_2}max$ should be measured directly.

The selection of an appropriate protocol for assessing functional capacity is of critical importance. When aerobic capacity is to be estimated from exercise time or peak work rate, protocols with large stage-to-stage increments in energy requirements should be avoided because of their weaker

relationship between oxygen uptake and work rate.¹⁵ The Balke¹⁶ and Naughton¹⁷ protocols, which involve only modest increases in treadmill elevation at a constant speed, are preferable for this purpose. Functional capacity can also be accurately determined with the use of "ramp" protocols in which small increments in work rate occur at intervals of 30 to 60 seconds. Regardless of the specific protocol chosen, the protocol should be tailored to the individual to yield a fatigue-limited exercise duration of ≈ 10 minutes.¹⁵ Shorter durations may produce a nonlinear relationship between \dot{V}_{O_2} and work rate, whereas durations > 12 minutes may cause subjects to terminate exercise because of muscle fatigue or orthopedic factors.

A frequent consideration in the assessment of functional capacity, especially in nonhospital settings, is whether to perform maximal or submaximal testing. Although maximal testing provides a more accurate determination of aerobic capacity, submaximal testing may be desirable in several situations. These include predischARGE testing of patients after myocardial infarction, assessment of frail or elderly subjects unaccustomed to vigorous exercise, and field testing of large numbers of subjects, especially when a physician is not on site. Submaximal testing typically relies on an extrapolation of maximal aerobic capacity from the work rate achieved at a given submaximal heart rate; thus, a significant potential for error exists because of the 10- to 12-beat-per-minute standard deviation in maximal heart rate in normal subjects. Even greater heart rate variation is encountered in patients with cardiopulmonary disease. When respiratory gases are not monitored, this potential error in estimating maximal heart rate will be compounded by the errors inherent in estimating aerobic capacity from the highest work rate achieved.

Another form of submaximal exercise testing that has become popular during the past decade is the 6- or 12-minute walk. Such tests have been widely applied to assess the responses of heart failure patients to pharmacological interventions; in these populations, the distance covered is also a powerful prognostic indicator.¹⁸ Additional advantages of such testing protocols are their simplicity, safety, negligible cost, and applicability to performing everyday activities. In patients with pulmonary disease, the distance covered in these timed-walk tests is highly reproducible ($r=0.86$ to 0.95) and correlates moderately well with peak \dot{V}_{O_2} ($r=0.52$ to 0.71).¹⁹ A similar correlation with peak exercise duration was found by Guyatt et al²⁰ in patients with heart failure. In patients who have pacemakers, a correlation of 0.74 with cycle ergometry performance was reported.²¹ The reproducibility of timed-walk tests is generally good, with intrasubject coefficients of variation averaging $< 10\%$.¹⁹ Nevertheless, modest improvements (usually $< 10\%$) on repeated testing necessitate at least 2 and preferably 3 tests to produce reliable results; most investigators use the best of these efforts as the true measurement. Whether these timed-walk tests can be substituted for the traditional but more demanding tests of functional capacity in assessing prognosis and responses to therapy requires further study. A 9-minute walk on a self-powered treadmill has also been used in patients with heart failure and has been found to be reproducible and to reliably separate patients with severe heart failure symptoms from those with mild to

moderate symptoms.^{22,23} Peak $\dot{V}O_2$ measured during maximal exercise on a self-powered treadmill has also been found to be reproducible and to approximate values measured on a motorized treadmill.²³

Application to Specific Populations

Coronary Artery Disease

The longstanding use of exercise testing in the diagnostic and prognostic evaluation of patients with suspected or known CAD has provided a large body of data on the utility of functional capacity assessment in such populations. Using the large Duke University database of patients undergoing diagnostic exercise testing, McNeer et al²⁴ observed that patients who exercised into stage 4 and beyond on a standard Bruce protocol (4.2 mph, 16% grade) with a negative or indeterminate ST-segment response had <15% prevalence of 3-vessel CAD and <1% prevalence of left main disease. Such patients had a 48-month survival rate of 95%. Conversely, the survival rate in patients who failed to complete stage 1 (1.7 mph, 10% grade) was only 78% at 36 months.²⁴ Even more marked survival differences as a function of exercise duration were noted in patients with known CAD. Numerous additional studies have verified the strong prognostic effect of exercise duration in patients with suspected or documented CAD.

Submaximal exercise testing is routinely performed in patients before hospital discharge after acute myocardial infarction. In this population, the MET level or exercise duration achieved is a powerful predictor of future adverse cardiac events; a commonly used marker for increased risk is the failure to achieve 5 METs during treadmill exercise. In these postinfarction studies, the highest mortality rate occurs in the subset that is unable to undergo exercise testing.^{25,26} In the Research on Instability in Coronary Artery Disease study, the major predictors of 1-year infarction-free survival in 740 men with unstable angina or non-Q-wave myocardial infarction who underwent predischARGE cycle ergometer exercise testing were the number of leads with ischemic ST-segment depression and peak workload attained.²⁷ Determination of functional capacity in CAD patients referred for cardiac rehabilitation is essential for developing an appropriate exercise prescription and in evaluating the results of training. Serial testing may be useful in revising the exercise prescription, evaluating improvement in aerobic capacity, and providing patient feedback. Meta-analyses of randomized cardiac rehabilitation trials have calculated a 20% to 25% reduction in cardiovascular deaths in patients enrolled in these exercise programs.²⁸ Improvement in exercise capacity after coronary bypass surgery generally parallels the completeness of revascularization.²⁹

Preoperative exercise testing is useful for predicting the risk of perioperative cardiac events in coronary patients undergoing major noncardiac surgery. The ability to achieve a high exercise workload is a consistent predictor of low postoperative cardiac risk, regardless of associated symptoms or ST-segment changes. Conversely, patients with an exercise capacity below ≈ 5 METs experience a significant risk of postoperative cardiac events, even in the absence of symp-

toms or ischemic ECG changes. Patients most likely to benefit from preoperative exercise testing are those with 1 or 2 of the following risk factors: diabetes mellitus, angina pectoris, pathological Q waves on ECG, or compensated heart failure.³⁰

Heart Failure

By definition, heart failure is the inability of the heart to maintain or increase CO at a rate commensurate with somatic aerobic requirements. Symptoms of heart failure may first become manifest as dyspnea or fatigue during activity. Therefore, it is appropriate to assess the functional capacity of patients with confirmed or suspected heart failure to determine whether, in fact, such impairment exists. It is well documented that resting parameters of ventricular function correlate poorly with exercise capacity.³¹ Moreover, in patients with heart failure, estimates of functional capacity such as exercise duration or peak work rate achieved are less reliable than direct measurements of gas exchange.³² Measurement of cardiopulmonary indexes during exercise has therefore become the standard for assessment of functional capacity in patients with heart failure. In patients with stable chronic heart failure, peak $\dot{V}O_2$ and VT are highly reproducible and hence recommended for evaluation of this unique population.³³

The New York Heart Association classification of functional capacity is imprecise because of its subjective nature. Although a class IV patient is generally easy to identify during a medical history and physical examination, it may be more difficult to distinguish a class II from a class III patient. Cardiopulmonary exercise testing offers an objective evaluation of functional capacity. Although some patients may not be able to achieve a true $\dot{V}O_{2\max}$, most patients can safely attain an anaerobic or ventilatory threshold. The VT is effort and protocol independent and usually is a minimal target in testing. If properly measured, VT is also reproducible in repeated testing and can be used as a clinical and prognostic tool.³⁴ VT can be adequately measured by the V-slope method in most heart failure patients. However, in patients with markedly impaired functional capacity (eg, peak $\dot{V}O_2 < 10 \text{ mL} \cdot \text{kg}^{-1} \cdot \text{min}^{-1}$), lactate production may be increased at rest, and identification of VT may be very difficult. The respiratory exchange ratio, defined by $\dot{V}CO_2/\dot{V}O_2$, provides an objective evaluation of the level of effort expended. Although the maximal respiratory exchange ratio varies significantly between individuals, a value > 1.1 has been suggested as subsidiary evidence that a true $\dot{V}O_{2\max}$ has been attained.³⁵ The commonly used Weber classification of exercise capacity in heart failure patients is provided in Table 1.³⁶ A derivation of the Weber classification has also been applied to the level of VT and to the increase in CO with activity. In addition to measurements of peak $\dot{V}O_2$ and VT, the value of $\dot{V}E/\dot{V}CO_2$ at peak effort and its rate of increase during exercise provide independent prognostic information in heart failure patients. A high value of $\dot{V}E/\dot{V}CO_2$ indicates excessive ventilatory drive and predicts a higher mortality.³⁷

In patients with heart failure, pulmonary disease may coexist. It may therefore be difficult to differentiate the source of exertional symptoms. Cardiopulmonary exercise

TABLE 1. Functional Impairment During Incremental Treadmill Testing in Heart Failure: The Weber Classification

Class	Severity	Peak $\dot{V}O_2$ mL · kg ⁻¹ · min ⁻¹	VT	CI max, L · min ⁻¹ · m ⁻²
A	Mild to none	>20	>14	>8
B	Mild to moderate	16–20	11–14	6–8
C	Moderate to severe	10–16	8–11	4–6
D	Severe	6–10	5–8	2–4
E	Very severe	<6	<4	<2

VT indicates ventilatory threshold; CI max, maximum cardiac index.

Adapted with permission from Weber et al, "Determination of aerobic capacity and the severity of chronic cardiac and circulation failure." (*Circulation*. 1987;76[suppl VI]:VI-40–VI-45.)

testing provides a means to distinguish cardiac from pulmonary-induced dyspnea (Table 2). Pulmonary dyspnea results from an impairment in ventilatory capacity; the patient may have to stop exercising because of an inappropriate rise in the minute ventilation (\dot{V}_E) relative to the maximum ventilatory capacity. The ratio of \dot{V}_E to maximum ventilatory capacity is referred to as the dyspnea index or ventilatory reserve index and rarely exceeds 50% unless pulmonary disease is present. Because cardiac dyspnea is a result of a poor cardiac reserve, both $\dot{V}O_2$ and VT will be low because of decreased oxygen delivery to the periphery. In this situation, however, the ventilatory reserve will be normal. Ventilatory or breathing reserve can also be expressed as \dot{V}_{Emax} times maximal voluntary ventilation and varies from 20% to 50% in normal individuals. A patient with a primary pulmonary limitation may not be able to achieve an anaerobic threshold. Minute ventilation in these patients will be excessive for the workload achieved. In addition, maximal voluntary ventilation is often reduced by obstruction or restriction to airflow. It is advisable in these instances to obtain pulmonary function tests to assess true maximal voluntary ventilation. Should arterial desaturation be suspected, the exercise test can be performed with simultaneous pulse oximetry.

Markedly impaired exercise tolerance places the heart failure patient in a high-risk category for a poor outcome. A peak $\dot{V}O_2$ of <10 to 12 mL · kg⁻¹ · min⁻¹ generally identifies a group of patients with a poor 1-year prognosis, and this group should be considered for cardiac transplantation evaluation.³⁸ In patients with a peak exercise $\dot{V}O_2$ of <14 mL · kg⁻¹ · min⁻¹, peak exercise systolic blood pressure and percent predicted $\dot{V}O_{2max}$ based on age- and sex-adjusted

TABLE 2. Cardiopulmonary Exercise Test Parameters Used to Differentiate Cardiac and Pulmonary Causes of Exertional Dyspnea

	Cardiac	Pulmonary
$\dot{V}O_{2max}$	Achieved, but low	Not achieved
Peak $\dot{V}O_2$	Reduced	Reduced
VT	Yes, but low	Rarely achieved
\dot{V}_{Emax}	<50% True MVV	>50% True MVV
SaO ₂	Normal	May drop to <90%
CO	Normal or low	Normal

VT indicates ventilatory threshold; MVV, maximal voluntary ventilation; and SaO₂, arterial oxygen saturation.

norms can aid further in risk stratification for possible cardiac transplantation.³⁹ Conversely, the presence of $\dot{V}O_2 > 14$ mL · kg⁻¹ · min⁻¹ has also identified a group of patients with a more favorable 1-year outcome.⁴⁰ Recently, a subset of patients with $\dot{V}O_2 < 14$ mL · kg⁻¹ · min⁻¹ has been identified who may have preserved cardiac function with exercise but who are extremely deconditioned.⁴¹ In this patient cohort, a program of directed cardiac rehabilitation can successfully improve peak $\dot{V}O_2$. Whether such improvement in peak $\dot{V}O_2$ translates into fewer hospitalizations or improved survival requires further study.

Valvular Heart Disease

In patients with noncritical valvular heart disease, exercise testing is often valuable in assessing atypical symptoms and functional disability. Such testing may be especially helpful in minimally symptomatic but physically inactive individuals, a common scenario among the elderly. In patients with aortic or mitral stenosis, exercise stroke volume is relatively fixed; in such patients, low functional capacity, an exaggerated heart rate response, and failure to augment systolic blood pressure with exercise are indicators that favor earlier surgery.¹ Although the decision to perform valve replacement in patients with aortic regurgitation is usually based on resting heart size and systolic function, exercise testing may be helpful in ambiguous situations. Because resting ejection fraction is a poor indicator of left ventricular function in mitral regurgitation, exercise testing with concomitant assessment of left ventricular performance may document occult ventricular dysfunction and suggest earlier surgical intervention. In patients with mitral valve prolapse and no valvular regurgitation at rest, the one third of patients who developed mitral regurgitation during supine cycle ergometry experienced a higher rate of subsequent syncope, heart failure, and progressive valvular regurgitation than those who did not.⁴²

Peripheral Arterial Disease

In patients with peripheral arterial occlusive disease, exercise testing offers an objective assessment of functional limitation. Quantification of total exercise time and time to the onset of claudication can be used to develop an exercise prescription and to monitor the response to training. Measurement of foot transcutaneous oxygen tension and ankle-to-brachial systolic pressure ratio before and after exercise may also help to determine the functional deficit and response to training. Large increases in maximal calf blood flow have been documented after such exercise programs.⁴³

Pacemakers

The development of rate-responsive and dual-chamber pacemakers has provided important alternatives to fixed-rate ventricular pacing. Several studies have documented that exercise CO and aerobic capacity are improved by these newer pacing modalities. However, it appears that the enhancement of chronotropic response contributes to this improvement more than AV synchrony.⁴⁴ Exercise testing may therefore be useful in deciding on the optimal pacing mode in a given patient.

TABLE 3. Uses and Limitations of Some Common Methods for Assessing Functional Capacity

	Types of Exercise			
	Maximal Without Respiratory Gas Analysis	Maximal With Respiratory Gas Analysis	Submaximal Without Respiratory Gas Analysis	6- to 12-min Walk
Variables of interest	Duration Estimated METs Peak HR and SBP Peak RPP Perceived exertion	Same as maximal plus these: peak or maximal $\dot{V}O_2$ VT Peak $\dot{V}CO_2/\dot{V}O_2$ Peak $\dot{V}E/\dot{V}O_2$ and $\dot{V}E/\dot{V}CO_2$ Peak $\dot{V}O_2$ /peak HR	Estimated METs duration Peak SBP (Peak HR usually fixed)	Distance walked
Utility	General fitness assessment Prognostic indicator in CAD patients Determining exercise prescription	Same as maximal plus these: gold standard for assessing aerobic fitness Classifies CHF severity and prognosis Decision tool for heart transplantation Quantifies response to medical or surgical interventions Differentiates cardiac vs pulmonary cause of dyspnea	Estimation of aerobic fitness when maximal testing is not feasible or is potentially unsafe (acute MI, before discharge) Can be used to formulate exercise prescription (if maximal testing cannot be done)	Estimation of aerobic fitness and endurance, especially in frail and elderly patients Measures response to medical or surgical interventions
Advantages	Modest cost Very large database	Best method to quantify aerobic fitness High reproducibility	Reduced risk vs maximal tests Modest cost	Negligible cost Very relevant to daily activities Good reproducibility Well tolerated, non-threatening
Limitations	Influenced by familiarity with testing, handrail use Often overestimates true aerobic capacity Reproducibility only modest	Requires more expensive equipment and greater expertise than other exercise tests Modest patient apprehension and/or discomfort Lesser ability to monitor patient's symptoms	Indirect assessment of maximal aerobic capacity Shares weaknesses of maximal testing without respiratory gases	Correlates only modestly with peak $\dot{V}O_2$ Influenced by test familiarity and motivation More difficult to determine whether maximal effort is achieved

SBP indicates systolic blood pressure; HR, heart rate; RP, rate-pressure product; VT, ventilatory threshold; CHF, congestive heart failure; MI, myocardial infarction; and CAD, coronary artery disease.

Congenital Heart Disease

Assessment of functional capacity has proved useful in a wide variety of congenital cardiac abnormalities in determining both the need for surgical repair and the response to treatment. In addition, exercise testing may be of value in confirming exertion-induced supraventricular or ventricular tachycardia in individuals with a suggestive history. Specific conditions in which exercise testing has proved useful include unoperated or palliated cyanotic defects, dilated cardiomyopathy, congenital complete AV block, chest pain, unexplained chest pain or syncope, and suspected tachyarrhythmias; after repair of aortic coarctation, tetralogy of Fallot, and Ebstein's anomaly; and after the Fontan operation.¹

Research Applications of Functional Capacity Assessment

In addition to its obvious value in the management of patients with a wide variety of cardiovascular disorders, the assessment of functional capacity is an important research tool. Many of the data on the utility of functional capacity measurement in the cardiac disorders previously discussed have been derived from cross-sectional and natural history studies. These studies typically have involved a single measurement of exercise capacity to determine the degree of exercise limitation imposed by a specific cardiovascular disorder and its prognostic significance.

In recent years, however, increasing attention has been directed toward using exercise testing to measure the therapeutic response to a lifestyle, medical, or surgical intervention. Serial assessment of exercise capacity presents greater challenges than the single determination used to characterize baseline function. Of greatest concern is defining the magnitude of change in functional capacity that represents a significant change from baseline. Although no universal criteria exist for test reproducibility, peak $\dot{V}O_2$ is generally considered reproducible if values vary <10% on separate days.⁴⁵ When respiratory gases are not monitored, exercise duration should vary <60 seconds on repeated testing; for a typical test lasting 10 minutes, this would translate to a difference of <10%. If 2 exercise tests do not meet these criteria for agreement, additional testing should be performed until these criteria are fulfilled. Because peak $\dot{V}O_2$ is generally more reproducible than treadmill time, gas exchange should be monitored in intervention studies whenever possible to minimize the standard deviation of the measurement, thereby reducing the sample size required. In a given patient with angina pectoris or claudication, exercise should be consistently terminated at the same level of chest or leg pain on repeated tests.

Attention to several methodological details during serial exercise testing can improve reproducibility. Because of diurnal variability in exercise capacity and ischemic threshold, with greater exercise tolerance in the afternoon than the morning,^{46,47} serial testing should be performed at the same time of day and ≥ 2 hours after eating to avoid the effects of food on myocardial oxygen demand and CO. Similarly, caffeinated beverages and smoking should be avoided during this interval. Although a temperature-controlled room is not essential, marked variations in ambient temperature should be avoided, and the laboratory should be well ventilated. Background medications should be taken in the same doses and time intervals before each test. Handrail support should be consistent between tests and should be minimized, especially when respiratory gases are not monitored. As noted previously, the exercise protocol should be individualized to the patient to achieve a duration of ≈ 10 minutes. Protocols with small, graded increments of work rate will generally provide the most accurate estimate of aerobic capacity when O_2 is not measured directly.^{15,45} A summary of the major uses and limitations of the common methods for assessing functional capacity is provided in Table 3.

Research Applications in Asymptomatic Populations

Over the past 4 decades, numerous studies have demonstrated that low levels of self-reported habitual physical activity are associated with increased risk of future cardiovascular disease, particularly CAD. This risk in sedentary subjects is approximately double that of active persons.⁴⁷ Given the extremely high prevalence of inactivity in the United States, the estimated number of CAD deaths attributable to sedentary lifestyle is second only to those from elevated cholesterol.⁴⁸

Physical fitness testing, by providing an objective assessment of functional capacity, is a more powerful predictor of cardiovascular disease mortality than is self-reported physical

activity, with risk ratios of 4 to 9 between the least-fit and most-fit categories. Numerous prospective studies have verified this relationship between fitness and cardiovascular risk in asymptomatic populations, even when submaximal exercise testing is used.^{49–52} In >13 000 men and women who underwent maximal treadmill exercise testing at the Cooper Clinic in Dallas, Tex, subjects in the lowest quintile of age- and sex-adjusted fitness suffered an 8- to 9-fold increased risk of cardiovascular death over a follow-up period of 8.2 years.⁵³ Perhaps the high relative risk of death in unfit subjects in the Cooper Clinic follow-up is the result of maximal rather than submaximal testing. Although it is certainly not cost-effective to perform exercise testing on the entire adult population to assess aerobic fitness, such testing might be judiciously applied to sedentary individuals with high coronary risk profiles to further stratify their cardiac risk and to motivate them to begin an exercise program. Follow-up exercise testing might then be used to document the beneficial effects of training.

In summary, measurement of functional capacity provides a valuable tool for diagnosis, treatment, and prognostic assessment in a wide variety of settings. The specific aspects of testing, such as the mode of exercise, protocol, end point, and analysis of respiratory gases, are highly dependent on the population being tested and the questions being addressed. Regardless of these specifics and despite the many recent advances in cardiac imaging, functional capacity assessment remains an important procedure in this era of managed care.

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