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Jonathan Myers, Ross Arena, Barry Franklin, Ileana Pina, William E. Kraus, Kyle McInnis, Gary J. Balady and on behalf of the American Heart Association Committee on Exercise, Cardiac Rehabilitation, and Prevention of the Council on Clinical Cardiology, the Council on Nutrition, Physical Activity, and Metabolism, and the Council on Cardiovascular Nursing

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Recommendations for Clinical Exercise Laboratories A Scientific Statement From the American Heart Association

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The present statement provides a guide to initiating and maintaining a high-quality clinical exercise testing laboratory for administering graded exercise tests to adults. Pediatric testing has been addressed separately.¹ It is a revision of the 1995 American Heart Association (AHA) "Guidelines for Clinical Exercise Testing Laboratories"² and is designed to complement several other AHA documents related to exercise testing, including the AHA/American College of Cardiology (ACC) guidelines for exercise testing,³ the AHA's "Exercise Standards for Testing and Training,"⁴ the AHA's "Clinical Competence Statement on Stress Testing,"⁵ and the AHA's "Assessment of Functional Capacity in Clinical and Research Settings."⁶

Exercise testing is a noninvasive procedure that provides diagnostic and prognostic information and evaluates an individual's capacity for dynamic exercise. Exercise testing facilities range from the sophisticated research setting to more conventional equipment in the family practitioner's or internist's office. Regardless of the range of testing procedures performed in any given laboratory, basic equipment, personnel, and protocol criteria are necessary to ensure the comfort and safety of the patient and to conduct a meaningful test.

Testing Room

Environment

Exercise testing equipment varies in size. The testing room should be large enough to accommodate all the equipment necessary, including emergency equipment and a defibrilla-

tor, while maintaining walking areas and allowing adequate access to the patient in emergency situations. It is also important that the laboratory comply with local fire standards and with procedures for other types of emergencies (eg, earthquake, hurricane).

The laboratory should be well lighted, clean, and well ventilated, with temperature and humidity control. A wall-mounted clock with a sweep second hand or a digital counter is useful. The examining table should have space for towels, tape, and other items needed for patient preparation and testing. A curtain for privacy during patient preparation is useful. Minimization of interruptions and maintenance of privacy allow the patient and laboratory personnel to concentrate on the testing procedure and add comfort to the patient.

To assess the level of effort, a large-print scale of perceived exertion⁷ (Table 1) should be mounted on the wall in clear view of the patient. Either the original (category) scale, which rates intensity on a scale of 6 to 20, or the revised (category-ratio) scale of 1 to 10 is appropriate as a subjective tool for exercise testing. Simpler 1-to-4 scales are preferable to quantify symptoms of angina or dyspnea.^{8,9} Dyspnea can also be measured by means of a visual analog scale that is valid and reliable.¹⁰ Handheld scales are useful during cardiopulmonary testing when the mouthpiece or mask may prevent speech. These scales should be clearly explained to the patient before testing is initiated.

In laboratories that perform ventilatory gas exchange, a thermometer, barometer, and hygrometer should be kept in

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Table 1. Rating of Perceived Exertion

Borg	Modified Borg
6	0—Nothing at all
7—Very, very light	0.5—Very, very weak
8	1—Very weak
9—Very light	2—Weak
10	3—Moderate
11—Fairly light	4—Somewhat strong
12	5—Strong
13—Somewhat hard	6
14	7—Very strong
15—Hard	8
16	9
17—Very hard	10—Very, very strong (almost maximum)
18	
19—Very, very hard	—Maximum
20	

The Borg RPE Scale®. From Borg GAV. *Borg's Scales of Perceived Exertion*. Champaign, Ill: Human Kinetics; 1999. Scales with updated instructions can be obtained from: borgperception@telia.com.

the room. Maintenance of an appropriate temperature is important because heart rate and perceived exertion rise with an increase in ambient temperature. In addition, cardiovascular responses become variable when humidity exceeds 60%, and the combination of heat and humidity will lower maximum performance. In general, a temperature range of 20°C to 22°C (68°F to 71.6°F) is considered comfortable for exercise. A cool, dry environment (50% humidity) enhances cutaneous heat exchange or loss and serves to dissipate excessive heat provoked by exercise. Circulating fans can assist in controlling room temperature and ventilation. If gas exchange measurements are being performed, barometric pressure and temperature should be measured, because gases expand with heat or with low barometric pressures and contract with cold or with high barometric pressures. Most commercially available automated cardiopulmonary testing systems will make adjustments for ambient conditions.

Equipment

Electrocardiogram

A suitable electrocardiographic recording system is essential for continuous monitoring of heart rhythm and evaluation of ischemic electrocardiographic changes during exercise and recovery. Equipment ranges from more sophisticated and costly computerized systems to simpler, more conventional types. Nonetheless, the instrument should meet the specifications set by the AHA.¹¹

When purchasing a highly specialized computer system, care must be taken to ensure that the frequency response accurately reflects ST-segment changes. It is necessary, therefore, to compare raw analog data with computer-generated data for validity. Continuous oscilloscopic monitoring of a minimum of 3 leads is recommended to optimally identify arrhythmia patterns; however, the ability to produce a 12-lead printed copy will enhance interpretation and is

highly recommended.¹² The 12-lead electrocardiogram (ECG) is essential for the accurate interpretation of particular arrhythmias, such as to distinguish ventricular tachycardia from supraventricular tachycardia with aberrancy. In addition, on rare occasions, significant ST-segment changes may be isolated to a particular lead set, such as the inferior leads. The Mason-Likar adaptation of the 12-lead ECG has been commonly used in the clinical setting.^{3,4,12} A standard 12-lead ECG should be performed before placement of the final limb leads, because lead placement with the Mason-Likar system may alter the inferior lead complexes to either mimic or hide previous Q waves. Electrocardiographic systems with built-in automatic arrhythmia sensing, which alerts the user to the occurrence of arrhythmias, are available commercially. Although not essential in every laboratory, these automatic arrhythmia detectors may be practical when the population being tested is at high risk.

Silver–silver chloride electrodes are recommended as the most dependable for minimizing motion artifact. Commercially available disposable electrodes vary in size and adhesive preparation. However, the importance of adequate skin preparation cannot be overlooked, regardless of the size or type of electrode used. Extra time spent on skin preparation will result in more stable recordings. Careful, accurate, and reproducible lead placement by staff will help to ensure standardization and reproducibility of ECGs. Lightweight, shielded cables will lessen motion artifact. In addition, cable systems that arise from a central box can be worn around the waist and further stabilize the electrocardiographic signal. Flexible knit “tube” shirts for stabilizing the electrodes and cables are also available.

Blood Pressure Monitoring

Manual auscultation is still the most feasible method of monitoring blood pressure during exercise and the easiest to use. A variety of automated blood pressure units are available, but these devices are expensive and may perform erratically at high exercise intensities because of motion. In addition, diastolic blood pressure may not be accurate when measured with these devices.¹³ If such systems are used, their reliability should be validated against manual cuff measurements within each respective laboratory before routine use, and distinctly abnormal hypertensive or hypotensive blood pressure recordings during exercise should be corroborated by manual recordings. A staff member should check abnormally high or low blood pressure readings.

The laboratory should have cuffs of various sizes, including large and pediatric.¹³ AHA recommendations for blood pressure cuff bladder sizes are presented in Table 2. Environmental and safety concerns have led to the replacement of most mercury manometers with digital or aneroid devices, and this has raised concerns about accuracy.¹⁴ The cuff should be placed at the level of the patient's heart, the proper cuff size should be used, and the equipment should be calibrated. Sphygmomanometers and cuffs, along with other testing equipment, should be cleaned and inspected on a regular schedule. As with any equipment that comes in contact with patients on a repeated basis, blood pressure cuffs

Table 2. AHA Recommendations for Blood Pressure Cuff Bladder Dimensions for Arms of Different Sizes

Cuff	Arm Circumference Range at Midpoint, cm	Arm Circumference Range at Midpoint, in
Adult	27–34	Up to 13.38
Large adult	35–44	13.7–17.3
Adult thigh cuff	45–52	17.7–20.4

There is some overlapping of the recommended range for arm circumferences; The AHA generally recommends that the larger cuff be used for borderline measurements.

Adapted from Perloff et al,¹³ with permission from Lippincott Williams & Wilkins. Copyright 1993, American Heart Association.

should be wiped with a cleaning solution each time they are used.

Ergometry

Treadmill

A treadmill should be electrically driven and should accommodate a variety of body weights up to at least 157.5 kg (350 lb). In addition, it should have a wide range of speeds, from a low of 1.6 km (1 mph) to a high of at least 12.8 km (8 mph). Elevation should be controlled electronically and should offer a variety of settings, from no elevation to 20% elevation. A dedicated 220-V outlet may be required along with heavy electrical cables that meet electrical safety standards. The treadmill platform should be a minimum of 127 cm (50 in) in length and 40.64 cm (16 in) in width. Models are available with side platforms to allow the patient to adapt to the moving belt before fully stepping onto it. For patient safety and stability, a padded front rail and at least 1 side rail are recommended. As much as possible, patients should be discouraged from holding the handrails, because doing so decreases the metabolic cost of the work rate. An emergency stop button should be easily visible and readily accessible to the staff and the patient when needed.

The metabolic cost of the treadmill work rate can be estimated from speed and grade by use of standardized equations (Table 3).⁸ Although this is common clinically, it is

associated with a significant degree of error,¹⁵ and these limitations should be considered when a patient's exercise capacity is estimated.

Bicycle

Cycle ergometry is an alternative to treadmill testing for those patients who have orthopedic, peripheral vascular, or neurological limitations that restrict weight bearing. It also remains the standard for testing in much of Europe. The cycle ergometer can also serve as a less expensive, portable substitute for treadmill testing. Work intensity can be adjusted by varying the resistance and cycling rate. Work rate can be calculated in watts or kilopond-meters per minute (kpm/min).

Two types of stationary bicycles are used for testing: Mechanically braked and electronically braked. Mechanically braked ergometers require that a specified cycling rate be maintained to keep the work rate constant. Electronically braked ergometers are more expensive and less portable but automatically adjust internal resistance to maintain specified work rates according to the cycling rate. These have become the standard for clinical testing when a cycle ergometer is used. Regardless of the type of stationary bicycle used, the ergometer must have the capability to adjust the work rate in increments either automatically or manually.

The cycle ergometer must include handlebars and a seat that adjusts for height. At the ideal seat height, the knee should be slightly flexed at full extension. For safety purposes, adaptable pedal grips should be included. In addition, meters, dials, or digital displays should be appropriately sized and placed for easy reading.

Physiological responses to exercise on a cycle ergometer differ from those obtained on a treadmill.^{8,15,16} Moreover, maximum oxygen uptake is 5% to 20% lower on a cycle ergometer than on the treadmill. Table 4 lists the approximate oxygen cost in metabolic equivalents (METs) for cycle ergometry relative to weight. As is the case with treadmill testing, there is a significant degree of error that must be considered when exercise capacity is estimated from the cycle ergometer work rate.

Table 3. Approximate Energy Requirements in METs for Horizontal and Grade Walking

% Grade	1.7 mph, 45.6 m/min	2.0 mph, 53.6 m/min	2.5 mph, 67.0 m/min	3.0 mph, 80.4 m/min	3.4 mph, 91.2 m/min	3.75 mph, 100.5 m/min
0	2.3	2.5	2.9	3.3	3.6	3.9
2.5	2.9	3.2	3.8	4.3	4.8	5.2
5.0	3.5	3.9	4.6	5.4	5.9	6.5
7.5	4.1	4.6	5.5	6.4	7.1	7.8
10.0	4.6	5.3	6.3	7.4	8.3	9.1
12.5	5.2	6.0	7.2	8.5	9.5	10.4
15.0	5.8	6.6	8.1	9.5	10.6	11.7
17.5	6.4	7.3	8.9	10.5	11.8	12.9
20.0	7.0	8.0	9.8	11.6	13.0	14.2
22.5	7.6	8.7	10.6	12.6	14.2	15.5
25.0	8.2	9.4	11.5	13.6	15.3	16.8

METs indicates metabolic equivalents.

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Table 4. Approximate Energy Requirements in METs During Bicycle Ergometry

Body Weight, kg (lb)	Power Output, $\text{kg} \cdot \text{m}^{-1} \cdot \text{min}^{-1}$ (W)						
	300 (50)	450 (75)	600 (100)	750 (125)	900 (150)	1050 (175)	1200 (200)
50 (110)	5.1	6.6	8.2	9.7	11.3	12.8	14.3
60 (132)	4.6	5.9	7.1	8.4	9.7	11.0	12.3
70 (154)	4.2	5.3	6.4	7.5	8.6	9.7	10.8
80 (176)	3.9	4.9	5.9	6.8	7.8	8.8	9.7
90 (198)	3.7	4.6	5.4	6.3	7.1	8.0	8.9
100 (220)	3.5	4.3	5.1	5.9	6.6	7.4	8.2

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Arm Ergometer

Arm exercise testing is a useful alternative for diagnostic testing of patients with lower-extremity impairment caused by vascular, orthopedic, or neurological conditions. In addition, arm ergometry is helpful for performing occupational evaluations in patients whose work primarily involves the arms and upper body. Dynamic arm exercise involves a smaller muscle mass than does leg ergometry for a given workload; however, arm exercise often necessitates the use of other muscles in the chest, back, buttocks, and legs for body stabilization, depending on exercise position and intensity.

Arm exercise testing can be performed with either mechanically braked or electronically braked arm ergometers. The former can be purchased separately as a specifically designed unit for graded arm cycling or can be adapted from standard bicycle ergometers by replacing the pedals with handles for cranking. Table 5 lists the approximate oxygen cost in METs for arm ergometry relative to weight.

Recommended protocols for arm ergometry testing require that the subject be seated in the upright position, with the fulcrum of the handle adjusted at shoulder height. The arm should be slightly bent at the elbow during farthest extension movements. Cycling speeds of 60 to 75 revolutions per minute must be maintained. Work rate increments of 5 to 10 W/min are typical, but this is best individualized on the basis of the subject's upper-body function. Testing end points are similar to those of other types of ergometry. $\dot{V}O_2$ requirements during arm cycle ergometry can be determined from formulas that take into account work rate, gender, and subject body weight.^{8,17} Other techniques used to test the upper body include rowing machines and air-braked arm/leg ergometers.^{18,19}

Oxygen uptake during any equivalent submaximal level (eg, 50 W) of arm work exceeds that of leg work. Accord-

ingly, the rate of increase in heart rate and blood pressure responses during arm ergometry is more rapid.¹⁷ Other physiological responses to dynamic arm exercise, for example, stroke volume and diastolic blood pressure, also differ from those of leg exercise.^{20,21} The sensitivity of arm exercise testing for detection of significant coronary artery disease is less than that of treadmill testing and is discussed elsewhere.²²

Equipment for Ventilatory Gas Exchange Analysis

Presently available computerized metabolic systems allow for the collection of ventilatory expired gas without a high degree of technical difficulty. The use of ventilatory expired gas analysis greatly improves both accuracy and reproducibility for assessing cardiopulmonary function compared with indirect estimation of oxygen uptake from work rate.^{15,23,24} In addition, the utilization of ventilatory expired gas analysis allows for the assessment of important submaximal cardiopulmonary responses, such as the ventilatory threshold. Although maximal and submaximal (ventilatory threshold) oxygen uptake is most frequently assessed, other variables such as the relationship between ventilation and carbon dioxide production ($\dot{V}E/\dot{V}CO_2$ slope), the partial pressure of end-tidal carbon dioxide, and oxygen uptake kinetics have also been shown to provide important prognostic and diagnostic information in some clinical populations.^{25–29} With respect to accepted clinical standards, the measurement of ventilatory expired gas is considered a class I indication by the AHA and ACC for the assessment of patients with heart failure who are being considered for heart transplantation and to identify the mechanism of exercise-induced dyspnea (cardiac versus pulmonary).³ With respect to the heart failure population, numerous investigations have consistently demonstrated the robust prognostic value of variables obtained from ventilatory

Table 5. Approximate Energy Expenditure in METs During Arm Ergometry

Body Weight, kg (lb)	Power Output, $\text{kg} \cdot \text{m}^{-1} \cdot \text{min}^{-1}$ (W)					
	150 (25)	300 (50)	450 (75)	600 (100)	750 (125)	900 (150)
50 (110)	3.6	6.1	8.7	11.3	13.9	16.4
60 (132)	3.1	5.3	7.4	9.6	11.7	13.9
70 (154)	2.8	4.7	6.5	8.3	10.2	12.0
80 (176)	2.6	4.2	5.8	7.4	9.0	10.6
90 (198)	2.4	3.9	5.3	6.7	8.1	9.6
100 (220)	2.3	3.6	4.9	6.1	7.4	8.7

expired gas analysis.^{25,30,31} In addition, these techniques allow for accurate quantification of the effects of pharmacological, surgical, and lifestyle interventions.^{32–34}

For these reasons, ventilatory expired gas analysis is being used more frequently in clinical and research settings. Although metabolic systems have become more user-friendly, the additional accuracy and information provided by this technology are dependent on some basic skills required of the clinician and technician responsible for calibration and maintenance of the system, as well as performance of the exercise test. In addition, the healthcare professional responsible for interpretation of the ventilatory expired gas data must have an understanding of the diagnostic and prognostic implications each variable provides, both independently and in combination. Adequate interpretation of the test requires knowledge of testing procedures as well. Consensus statements addressing the utility of ventilatory expired gas analysis have been published recently by several well-respected national and international organizations.^{35–39}

Ancillary Imaging

Stress echocardiography and cardiac radionuclide imaging improve the sensitivity and specificity of the standard exercise ECG in patients with suspected myocardial ischemia and allow for visualization of ventricular function. These imaging techniques are particularly valuable in patients with baseline ST segment abnormalities (left bundle-branch block, left ventricular hypertrophy, Wolff-Parkinson-White syndrome, paced rhythms, or digoxin use). In addition to the need for qualified personnel and the substantial cost of the equipment, other factors must be considered if ancillary imaging is to be performed in conjunction with exercise or pharmacological stress. The use of a gamma camera for radionuclide images or a cardiac ultrasound machine for stress echocardiograms will require increased space to accommodate this equipment. For exercise echocardiography, the bed or gurney should be in close proximity to the treadmill or cycle ergometer and parallel to it lengthwise to facilitate transfer of the patient. Dedicated electrical outlets or a 220-V line may be necessary as well. Institutional radiation safety committee guidelines must be followed carefully. If a large volume of stress echocardiograms are to be performed, a platform or bed with a cutaway mattress for easier imaging can be helpful. Detailed guidelines for stress echocardiography and cardiac radionuclide imaging are available elsewhere.^{40,41}

Blood Analysis

Arterial blood samples allow for the direct measurement of SaO₂, PaO₂, PaCO₂, pH, and lactate, as well as an accurate assessment of physiological dead space ventilation when expired gas analysis is used. Arterial blood gases typically are sampled from the radial artery, whereas lactate can be measured rapidly with a handheld unit with a finger-stick blood sample. Pulse oximetry (SpO₂) permits a reasonably accurate estimation of SaO₂, which decreases the need for arterial blood analysis in patients with pulmonary disease who are undergoing an exercise test for the assessment of dyspnea with exertion. Recent data suggest that B-type natriuretic peptide measurements during exercise testing may

improve diagnostic and prognostic accuracy^{42–44}; however, more data are needed before this can be recommended for clinical use. Handheld units that require a finger-stick blood sample are available for the rapid measurement of B-type natriuretic peptide.

Cardiac Output

There are currently several commercially available systems that estimate cardiac output noninvasively at rest and during exercise. Widespread use of these systems is not common in today's testing environment. These systems present an interesting approach to the assessment of stroke volume, cardiac output, and other measures of cardiac performance and are sometimes used in clinical research; however, their accuracy, their diagnostic and prognostic utility, and the patient populations in which they are most useful require further study.

Emergency Preparation

Procedures

Although exercise testing is a very safe procedure, the risk of testing varies with the patient population being tested. Studies documenting the safety of exercise testing are outlined below. Because the majority of diagnostic laboratories perform exercise tests in a population with a higher prevalence of coronary disease, all testing facilities must have equipment, drugs, and personnel trained to deliver appropriate emergency care.

In some cases, exercise testing is performed outside of the hospital or clinical setting. For instance, maximal or submaximal exercise tests may be performed in the preventive exercise setting (eg, a health club) to develop individualized exercise prescriptive guidelines or to evaluate change in cardiorespiratory fitness over time. In such cases, guidelines for emergency readiness and supervision by qualified healthcare professionals such as those stated in this document and in the joint position papers from the AHA and the American College of Sports Medicine^{45,46} should be followed. In general, these guidelines call for the following: (1) Risk stratification of persons to be tested to determine the appropriate level of medical supervision needed during testing; (2) a written emergency plan that is rehearsed quarterly or with enough regularity that it runs effectively if needed; the plan should also describe evacuation of unstable patients by a specified route for rapid transfer to hospital emergency facilities; (3) the presence of an automated external defibrillator; and (4) trained staff who are well versed in recognizing abnormal hemodynamic responses and/or signs and symptoms of ischemic heart disease. Regardless of the setting, all exercise laboratories should have a written emergency plan appropriate to the individual facility. Moreover, AHA protocols for basic and advanced life support should be followed as appropriate.⁴⁷

Equipment and Drugs

Table 6 lists the minimum emergency equipment necessary in an exercise testing laboratory. If intubation becomes necessary, suction equipment, a laryngoscope with blades of various sizes, and intubation equipment should be readily available. If a more extensive equipment cart is located in an

Table 6. Emergency Equipment

Defibrillator (portable); automated external defibrillator recommended
Oxygen tank (portable, if possible, for transport)
Nasal cannula, Ventimask, nonbreathing mask, O ₂ mask
Airways: oral (OPA) and nasal (NPA)
Bag-valve-mask hand respirator (Ambu bag)
Syringes and needles
Intravenous tubing, solutions, and stand
Adhesive tape
Suction apparatus and supplies (eg, gloves, tubing)*

OPA indicates oropharyngeal airway; NPA, nasopharyngeal airway.

*May be immediately available when a team arrives in certain centers.

area other than the testing area, a specific plan for rapid accessibility to the cart should be clearly defined. A defibrillator should be in every exercise laboratory and should be tested on a daily basis and recorded in a log for quality control. The AHA's classification of drugs most commonly used in a life-threatening emergency is listed in Table 7.⁴⁷

Patient Preparation

In the current practice environment, a written referral for exercise testing should be provided by the physician requesting the assessment with a brief description of the diagnosis (confirmed or suspected), the reason for testing, a list of the patient's medications, medical history, and patient contact information. With regard to medications, information about the dose and time taken should be made available. Ideally, after the appointment is made, detailed written instructions should be given to the patient before the day of the exercise test. Written material should state the date and time of the exercise test, directions to the laboratory, and contact information. Abstinence from food for 3 hours before regular testing and 8 hours before a radionuclide imaging study is suggested. Clothing should be comfortable and loose, and footwear should be sturdy and comfortable. If the patient is prescribed medications, the instructions should include a request for a list of drugs and dosing to be brought to the testing center. Instructions regarding medication use on the day of the exercise test should also be included. Medications taken the day of the test should be confirmed. Certain antiischemic pharmacological agents may decrease the sensitivity of exercise tests used to detect ischemia. Although tapering of medications for several hours or days before testing is no longer considered necessary for most patients,³ it may be appropriate for some patients to withdraw certain medications, using an appropriate tapering regimen, before the exercise test. Conversely, if the intent of the exercise test is to determine the effectiveness of pharmacological therapy or functional capacity assessment, the patient should continue taking all medications before the exercise test.⁴⁸ If the patient is not provided with written instructions, he or she should be contacted by telephone to discuss the aforementioned issues. Involvement of the referring physician is critical in situations in which plans may require the withholding of daily medications. The AHA provides patient education materials with details of exercise testing procedures and rationale.

Table 7. Emergency Drugs and Solutions

Required drugs
Atropine
Lidocaine
Adenosine
Sublingual nitroglycerin
Diltiazem
Intravenous metoprolol
Diltiazem
Epinephrine
Amiodarone
Dobutamine
Verapamil
Dopamine
Vasopressin
Chewable aspirin 325 mg
Intravenous fluids
Normal saline solution (0.9%)
D ₅ W bolus
For laboratories performing dipyridamole (adenosine) testing
Theophylline
For laboratories performing contrast echocardiography, the following should be available to treat acute allergic reactions
Diphenhydramine
Dexamethasone
Albuterol
EpiPen

The Day of Exercise Testing: Patient Instructions and Discussion

To optimize the value of diagnostic testing, patient cooperation is essential. In most cases, an adequately informed patient will give a maximum of effort and thus provide the most information for an optimum interpretation. A comprehensive dialogue between the patient and healthcare professional may be particularly important for individuals unaccustomed to exercise and diagnosed with cardiovascular or pulmonary disease. Concern that high levels of physical exertion will precipitate an adverse event may cause the patient to put forth a submaximal effort. Discussion regarding the safety of exercise testing, the monitoring procedures used, and the importance of the exercise data obtained may alleviate any apprehension the patient may have. Specific instructions should also be given on how to perform the exercise test, with a brief demonstration of the test procedure. Lastly, all of the patient's questions must be answered thoroughly before the test.

As a part of patient instructions/discussion, written informed consent should be obtained and witnessed by personnel who can accurately describe the test and potential risks. Translation should be provided for non-English-speaking patients. The informed consent should be included in the exercise test record. An example of an informed consent is presented in Appendix 1. Language regarding protection of patient health information, both specific to an institution and

for the Health Information Portability and Accountability Act (HIPAA), is required. The language used in the consent form can be modified to fit the requirements of a particular laboratory.

The Day of Exercise Testing: Patient Preparation

A brief history and physical examination should be conducted before testing to determine medical/surgical history, cardiovascular risk factors, and prior diagnostic tests and to perform a brief cardiovascular and pulmonary examination. This is important because the diagnostic accuracy of the test is directly related to the pretest probability of disease.³ The last dosing of cardiovascular drugs should be noted on the record. Conditions that would potentially preclude or limit performance of the exercise test (ie, orthopedic/neurological restrictions, signs/symptoms of unstable angina, decompensated heart failure, or psychiatric conditions such as anxiety and depression) should also be determined. A sample pretest history and physical form is shown in Appendix 2. In addition, information about usual physical activity habits and perceived functional capacity will aid the laboratory staff in selecting an appropriate testing protocol. In general, for younger individuals with a history of exercise training, more aggressive testing protocols may be preferred (more aggressive increase in workload from 1 stage to the next). For older and/or sedentary individuals, as well as patients with moderate to severe cardiovascular or pulmonary disease, more conservative testing protocols should be considered. Ideally, the exercise test should result in a maximal level of exertion within 8 to 12 minutes.^{3,8,35} Assessment of a subject's perceived functional capacity by an activity-specific questionnaire, in conjunction with other baseline variables, has been shown to accurately predict peak exercise capacity.^{49,50} This approach may be used to individualize a subject's exercise protocol and increase the likelihood of completing the test within an appropriate timeframe.

Skin Preparation

No electrocardiographic recorder can replace good skin preparation as part of electrode placement. For the interface between the skin and electrode to be optimal, skin resistance should be reduced to 5000 Ω or less. Fortunately, most commercially available exercise electrocardiographic recorders have an AC-impedance meter built into their interface to test for this. Proper skin preparation requires that a superficial layer of skin be removed. This is even more important in older patients, who often have thinner, more fragile skin. To accomplish this, the areas where electrodes will be applied should be shaved if significant hair is present. Alcohol-saturated gauze should be used to clean and remove oil from the skin. When the alcohol has evaporated, the exact electrode-placement areas should be marked with a felt-tipped pen. These marks can then be rubbed with fine sandpaper or commercially prepared abrasive tape to remove the superficial layer of skin. It is critical that electrodes for exercise testing possess a metal interface and are sunken, creating a column that is typically filled with an electrolyte

Table 8. Angina and Dyspnea Scales

Angina scale	
1+	Onset of discomfort
2+	Moderate, bothersome
3+	Moderately severe
4+	Severe; most pain ever experienced
Dyspnea scale	
1+	Mild, noticeable to patient but not observer
2+	Mild, some difficulty, noticeable to observer
3+	Moderate difficulty but can continue
4+	Severe difficulty, patient cannot continue

solution. Many disposable electrodes that fulfill these requirements are available. After electrode placement, the technician can lightly tap the electrode to assess adequacy of skin preparation (the tap should not create noise on the ECG). In addition, efforts should be taken to minimize motion at the electrode-cable interface. This may be achieved by creating stress loops with precut tape strips or securing the cables centrally with an elastic belt worn around the waist. Disposable mesh vests placed on the upper torso can help secure the electrodes.

Resting Data

A standard resting 12-lead ECG, heart rate, and blood pressure should be recorded in both the supine and standing (or sitting for cycle ergometry) positions before testing. This is necessary to determine the presence of any ECG and/or hemodynamic abnormalities that might contraindicate the test and to determine any changes that occur due to body position. If gas exchange analysis is being performed, resting values should be recorded with the patient at rest for at least 2 minutes or until a stable baseline is achieved (ie, approximate oxygen uptake of 3.5 mL O₂ · kg⁻¹ · min⁻¹ and respiratory exchange ratio <0.80). Should the respiratory exchange ratio exceed 1.0, a stable baseline can usually be achieved after the patient sits for a few minutes while breathing quietly and is given reassurance by the testing personnel.

Exercise Data

Heart rate, ECG, and blood pressure should be monitored continuously throughout the exercise test. Additionally, heart rate, ECG, blood pressure, and the patient's perceived exertion and symptoms (dyspnea/angina) should be recorded at regular intervals throughout the exercise test. The recommended recording intervals during the exercise test for these variables are as follows: (1) Heart rate and ECG—the last 5 to 10 seconds of each minute; (2) blood pressure—the last 30 seconds of each stage for interval protocols or the last 30 seconds of each 2-minute interval for ramping protocols; and (3) perceived exertion—the last 5 seconds of each minute. Dyspnea or angina should be recorded when they initially occur, and their progression should be recorded with 1-to-4 scales (Table 8).^{8,9} Each of these responses should be recorded at peak exercise. It may be preferable to record the ECG just after the blood pressure is taken to reduce electrocardiographic signal

artifact. A copy of the ECG should either be stored (as part of a digital workstation) or a hard copy should be printed at the recommended intervals during the exercise test. Abnormal electrocardiographic responses (ie, arrhythmias, ST-segment shifts) should be recorded as they occur. In addition, the patient's appearance should be monitored for changes in skin color, alertness, coordination, and responsiveness during exercise. Termination criteria for exercise testing include patient request, moderate to severe dyspnea or angina, specific electrocardiographic changes (ie, arrhythmias or ST-segment shifts), and abnormal blood pressure responses. A detailed description of absolute and relative exercise test termination criteria is given in the ACC/AHA's guidelines for exercise testing.³ A sample data recording form is shown as Appendix 3. Heart rate, blood pressure, and electrocardiographic responses during recovery are included because abnormalities that occur during the postexercise period provide valuable diagnostic and prognostic information.⁵¹⁻⁵⁵ The patient should be monitored carefully until heart rate, blood pressure, and the ECG have returned to near-baseline levels. If the exercise test was terminated because of subject request, the clinician should inquire as to the exact reason in a nonleading fashion. Moreover, if the patient has experienced any discomfort, monitoring should continue until significant symptoms have resolved. If symptoms and/or abnormal signs persist beyond 15 minutes in recovery, the supervising physician should evaluate the patient and recommend further observation or treatment. Having the patient recover in a supine position may accentuate ST-segment changes, and it is important that such changes be recorded for diagnostic purposes. If ST-segment changes occur only in recovery or worsen in recovery, this observation must be included in the report to the referring physician.

Personnel

Healthcare professionals from several disciplines may possess the training and experience required to perform competently in an exercise testing laboratory. Staff members may include exercise physiologists, nurses, nurse practitioners, physicians' assistants, and medical technicians. Appropriate training and information about the cognitive and performance skills necessary to competently supervise exercise tests are available in published guidelines.⁵ The attainment of advanced training/certifications, such as the American College of Sports Medicine Exercise Specialist or Registered Clinical Exercise Physiologist, should be considered by exercise testing laboratory personnel. All staff members must have received training in basic life support,⁴⁵ and training in advanced cardiac life support is encouraged. Recommendations for exercise test supervision are discussed in the section on "Supervision/Staffing of Exercise Testing Laboratories" below.

The medical director of the exercise laboratory is responsible for the organization and supervision of the laboratory and its policies. The physician should also ensure that the laboratory is properly equipped and that the staff is appropriately qualified and trained. The medical director should make

sure that the staff is well prepared for response to emergencies and that a regular emergency practice with documentation is conducted. The documentation of emergency practices should be kept in a file for later review. The physician is responsible for interpreting the data, suggesting further evaluation or additional techniques for testing, if needed, and delivering appropriate emergency care when necessary. Requirements for physician competency in this area have been outlined by the ACC and AHA.⁵ In certain cases, the patient should remain in the testing laboratory until the supervising physician reviews the test, determines appropriate follow-up, and counsels the patient. Accurate and timely written interpretation of the exercise test results should be available, ideally in 72 hours or less. A preliminary test reading, however, should be available immediately. If the test results are highly abnormal, the referring physician should be notified as soon as possible.

Supervision/Staffing of Exercise Testing Laboratories

It is the consensus of this writing group that the use of specially trained nonphysician healthcare professionals is appropriate to supervise clinical exercise testing, if the individual supervising the test meets competency requirements for exercise test supervision,⁵ is fully trained in cardiopulmonary resuscitation, and is supervised by a physician skilled in exercise testing who is immediately available and later reads over the test results. These allied health professionals typically include exercise physiologists, nurses, nurse practitioners, and physician assistants but may include other health professionals. Because this issue has been the topic of significant debate in the past, it is addressed in some detail in this section.

Diagnostic exercise testing necessarily involves a bout of very hard to maximal physical exertion, performed through a progressive or incremental protocol to volitional fatigue or until the occurrence of abnormal clinical signs or symptoms that may dictate test termination. Pathophysiological evidence suggests that in selected individuals with known or occult coronary artery disease, the increased cardiac demands may precipitate plaque rupture and acute coronary thrombosis or myocardial ischemia and threatening ventricular arrhythmias, which, in extreme cases, may be harbingers of ventricular tachycardia or fibrillation. Thus, the recommendation for direct medical supervision of peak or symptom-limited exercise testing probably stems, at least in part, from the putative increased risk of cardiovascular events during the procedure. A contemporary survey on practice patterns of exercise testing within the Veterans Affairs Health Care system revealed that considerable variation exists in terms of whether direct physician presence is required during exercise testing. A physician was present during 73% of all exercise tests; however, 21% of the respondents reported that physician presence was required "only for high risk patients" (p 253).⁵⁶ Although the most conservative approach would employ the physical presence of a physician during all exercise tests, this recommendation requires a critical evaluation of complication rates with supervision by

highly trained allied health personnel versus direct physician monitoring, especially in high-risk patient subsets, as well as a review of state-specific regulations regarding the scope of practice of nonphysicians.

Complication Rates of Exercise Testing

Although exercise testing is considered a safe procedure, associated cardiovascular events have been reported. A previous review summarizing 8 studies of estimates of sudden cardiac death during exercise testing revealed rates ranging from zero to 5 per 100 000 tests (0.005%).⁵⁷ Multiple contemporary surveys indicate that the risks of a complication that requires hospitalization (including serious arrhythmias), acute myocardial infarction, or sudden cardiac death during or immediately after an exercise test are $\leq 0.2\%$, 0.04% , and 0.01% , respectively.⁸ On the basis of these surveys, the event rate (often defined as death or an event serious enough to require hospitalization) is usually considered to be approximately 1/10 000.

Expanded Role for Allied Health Professionals

Historically, exercise tests were directly supervised by physicians more than 90% of the time⁵⁸; however, over the past 3 decades, cost-containment issues and time constraints on physicians have encouraged the use of specially trained nurses, nurse practitioners, clinical exercise physiologists, exercise technicians, physician assistants, and physical therapists to administer selected exercise tests, with a physician immediately available for patient assessment or emergencies that may arise. Indeed, numerous reports and empirical experience suggest that many hospitals, medical centers, and private physician practices now use highly trained and/or certified nonphysicians in the direct supervision of stress testing, with and without concomitant myocardial perfusion imaging.

In 1979, the AHA first endorsed the concept that exercise testing may, in some instances, be delegated to "experienced paramedical personnel" (p 426A).⁵⁹ This recommendation has evolved so that today, the degree of subject supervision needed during a test is generally made by the supervising laboratory physician or his or her designated staff member on the basis of the subject's clinical status, medical history, and standard 12-lead ECG performed immediately before testing.⁴ A defibrillator, other life support equipment, medications, and personnel trained to provide advanced cardiopulmonary resuscitation must be readily available. Moreover, guidelines from the American College of Sports Medicine suggest that highly trained allied health professionals may provide exercise test supervision for patients at increased risk if a physician is in close proximity and readily available should there be an emergent need.⁸ The rationale for this recommendation stems from several lines of evidence highlighting the low complication rate associated with nonphysician supervision of exercise stress testing.

A summary of the complication rates of exercise testing from 1969 to 1995, which included 12 different reports involving nearly 2 million exercise tests, addressed the

morbidity and mortality rates associated with physician versus nonphysician supervision.⁶⁰ Subjects included individuals with and without a history of cardiovascular disease, athletes, and patients with a history of malignant ventricular arrhythmias. Complications were defined as the occurrence of acute coronary thrombosis or threatening arrhythmias during exercise testing (eg, ventricular fibrillation, ventricular tachycardia, or bradycardia) that mandated immediate medical treatment (cardioversion, use of intravenous drugs, or closed-chest compression). One study evaluated the safety of exercise testing by physical therapists for patients with and without documented coronary artery disease.⁶¹ The associated morbidity and mortality rates were 3.8 and 0.9 per 10 000 tests, respectively. Using a nurse-supervised exercise laboratory, Lem and associates⁶² reported 12 complications and no deaths during 4050 tests; however, another series reported 3 deaths among more than 12 000 exercise tests conducted by specially trained nurses.⁶³ In a summary of their 13-year experience using exercise physiologists for the supervision of exercise testing, Knight and associates⁶⁴ reported no fatalities, 4 myocardial infarctions, and 5 episodes of ventricular fibrillation in 28 133 tests. Franklin et al⁶⁰ reviewed 18 years (1978–1995) of exercise testing experience by nonphysicians (highly trained nurses and certified exercise physiologists credentialed in basic cardiopulmonary resuscitation and advanced cardiac life support) who performed 58 047 tests that included a significant subset ($\approx 15\%$ to 20%) of higher-risk patients. There were 14 complications (including 2 fatalities), for an event rate of 1 per 4146 exercise tests.

More recently, others have reported similarly low complication rates in populations tested by experienced technicians, exercise physiologists, physician assistants, and registered nurses, including stress echocardiography.^{65–69} In a prospective pilot investigation of nonphysician supervision of patients with severe chronic heart failure (left ventricular ejection fraction ≤ 0.35), Squires et al⁷⁰ reported only 1 serious complication (an episode of ventricular fibrillation that was successfully reverted without adverse sequelae) during 289 cardiopulmonary exercise tests. Another preliminary report⁶⁸ noted that exercise and pharmacological stress testing could be conducted safely by specially trained nurses and exercise physiologists in selected high-risk patients with implantable cardioverter defibrillators. Because pharmacological stress testing is generally relegated to physicians or selected medical staff (eg, registered nurses), this practice should be compatible with institutional policy and state regulations. Thus, there is ample evidence to support contemporary guidelines that state that exercise testing "can be performed safely by properly trained allied health professionals working directly under the supervision of a physician, who should be in the immediate vicinity" (p 264).^{70a} Moreover, several reports now suggest that highly trained physiologists and technicians can also provide an accurate preliminary interpretation of the exercise ECG, in excellent agreement with senior physician and/or cardiologist consultant overreads.^{65–67,71}

Competency Considerations

Although the cardiovascular complications associated with exercise testing appear to be infrequent ($\leq 0.2\%$),⁸ the ability to maintain a high degree of safety depends on knowing and identifying relative and absolute contraindications, knowing when to terminate the test, and being prepared for any emergency that may arise. These competencies can be achieved by highly trained allied health professionals provided that physician staff is readily available for patient assessment, consultation, and management of emergencies that may arise. Nonphysicians can accurately review the medical history and baseline ECG and provide a timely interpretation of exercise-induced signs and symptoms, terminating an exercise test at an appropriate intensity level.⁵ This premise is supported by comparative data and recent reports showing that the incidence of cardiovascular complications is no higher with experienced paramedical personnel than with physician supervision of exercise tests.⁶⁰

Although the use of specially trained and/or certified healthcare professionals for supervision of clinical exercise testing can be a safe and cost-effective alternative for many hospitals and medical centers, this practice should be compatible with state licensure regulations and statutory definitions for the practice of medicine before it is implemented.⁷² Otherwise, there may be the potential for detrimental consequences, raising medical-legal risks for the physician/institution as a function of delegation of licensed authority.

For details regarding the minimum education, training, experience, and cognitive and procedural skills necessary for competent performance and interpretation of exercise testing, the reader should refer to the ACC/AHA/American College of Physicians' "Clinical Competence Statement on Stress Testing."⁵ For internal medicine and family practice residency programs that provide training in exercise testing, often as an elective, a minimum of 4 weeks or the equivalent should be devoted to this rotation to achieve competence in both supervision and interpretation. It has been suggested that such trainees perform at least 50 exercise stress tests to qualify for diagnostic exercise testing in private practice and that physicians perform at least 25 exercise tests per year to maintain their competence.⁵

Report of Test Results

The written report should be completed in a timely fashion and should contain the information necessary to assist the physician in clinical decision making. Reporting the test results as *positive* or *negative* should be avoided; it is preferable to use the terms *normal* or *abnormal*⁷ and the precise responses should be reported. Abnormalities should include data that place the patient outside his or her expected performance, including impaired functional capacity, which is a common but frequently ignored test result. The demographic data, date of test, reason for the test, and protocol used should be clearly identifiable. The report should include the peak work rate achieved by the patient in METs or $\dot{V}O_2$, peak heart rate and blood pressure, and any abnormal signs or symptoms that occurred during or after the test. Whether

exercise capacity was determined by estimated METs or by directly measured $\dot{V}O_2$ should be specified. If it was necessary for the patient to hold the treadmill handrails, the report should indicate this. Because the referring physician may not be familiar with normal standards, appropriate reference values for age and gender should be provided. The perceived exertion level achieved should be recorded. The electrocardiographic data should consist of rest, abnormal exercise changes, and return to baseline. Occurrence of arrhythmias must be noted as well. If ischemia was demonstrated by electrocardiographic changes, the time and heart rate at which the changes initially occurred should be specified. If gas exchange measurements were made, peak oxygen uptake (in mL of O_2 per minute and mL of $O_2 \cdot kg^{-1} \cdot min^{-1}$) should be recorded, and the ventilatory threshold (if achieved) should be determined. With modern ECG and gas exchange testing systems, detailed summary reports can be issued that allow the physician to add comments as needed. An overall integrated score (such as the Duke Treadmill Score) should be included as part of the report.³ A summary impression of the findings must be included and should be made part of the patient's permanent record. Any recommendations for further diagnostic testing can be included as well. If pharmacological or imaging agents or echocardiography is added to the exercise test, appropriate reports should include findings, prognostic characteristics, comparisons with the most recent test, etc. An example of an exercise test summary report is shown in Appendix 4.

Quality Control

Exercise laboratories must have an active quality assurance plan that should address and enforce practice for emergency situations. The plan should also assess staff performance during emergencies. Other quality control issues include the need to keep laboratory records that indicate regular maintenance and nonscheduled repairs of testing equipment, calibration logs, defibrillator testing, and review of emergency medications and their expiration dates. Staff education, whether formal (eg, in the form of continuing education credits or American College of Sports Medicine certification) or informal, should be documented. Hospital-based laboratories will need to review quality control issues for certification by the Joint Commission on Accreditation of Healthcare Organizations.

Treadmill, Cycle Ergometer, and Metabolic System Calibration

Calibration of the treadmill and cycle ergometer (both leg and arm) should be performed on a monthly basis. Specific directions for calibration and preventive maintenance are typically included in the treadmill or ergometer operation manual provided by the manufacturer. Each laboratory should record dates that calibrations are performed. These records are an important part of quality assurance procedures.

Treadmill Speed

Calibration of treadmill speed requires knowledge of the belt length, which can be obtained from the manufacturer or

measured with a tape. The treadmill speed can be calibrated by counting the number of rotations of the treadmill belt per unit of time. Using a mark on the treadmill belt as a reference, the number of belt revolutions in 1 minute can be counted, and, knowing the length of the belt, the actual miles per hour calculated by:

$$\frac{\text{Belt length (inches)} \times \text{number of revolutions per minute}}{1056}$$

(1056 = conversion of inches per minute to miles per hour).

The value obtained is the treadmill speed in miles per hour. If the speed indicator does not agree with this value, adjust the meter to the proper setting. On some treadmills, a calibration adjustment screw is found in a small opening in the front of the control panel. If not available, the manufacturer should be contacted. The calibration procedure should be repeated for several different speeds to ascertain accuracy across commonly used protocols in a given laboratory.

Treadmill Elevation

Treadmill elevation is calibrated by measuring a fixed distance on the floor and determining the difference in height of the treadmill over the fixed distance. The following specific procedures are performed:

1. With the use of a carpenter's level, ensure that the treadmill is resting on a level surface. Set the treadmill elevation to 0% grade. If the elevation does not read 0% when it is level, adjust the potentiometer until it does.
2. Mark 2 points 50 cm (20 in) apart along the length of the treadmill.
3. Elevate the treadmill to its metered reading of 20% grade and measure the distance of each of the 2 points to the floor.
4. Divide the difference between the 2 heights by 20. The results should be 0.20 or 20% when the elevation is properly calibrated. If the result is not 20%, adjust the elevation meter potentiometer so that it displays the calculated elevation percentage. A check of 5%, 10%, and 15% grade readings is recommended to ensure the validity of intermediate positions.

Speed and elevation should be calibrated without a subject on the treadmill. It is recommended, however, that a moderately heavy subject (75 to 100 kg) walk on the treadmill after calibration to ensure that the calibrations remain accurate when the treadmill is in use. Speed should remain unchanged regardless of the weight of the individual on the treadmill.

After approximately 1000 hours of use, the treadmill should be serviced, which should include lubricating the motor bearings, checking the variable speed belt for wear, centering the belt, greasing the chain drive, and cleaning and lubricating the gears. Service and maintenance schedules should be available from the manufacturer.

Bicycle Ergometer Calibration

Because the work rate on a mechanically braked ergometer depends not only on the resistance but also on the cycling rate

in revolutions per minute, it is essential that a counter quantify this factor. It is also important that the belt tension be adjusted appropriately and that the flywheel be cleaned to ensure smooth operation. Electronically braked ergometers are more difficult to calibrate and require special instruments generally not available to the individual purchaser, so calibration is usually provided by the manufacturer or by the institutional biomedical engineering department.

To check the calibration on a mechanically braked cycle ergometer, the belt should be removed from the wheel. The mark on the pendulum weight should be set at "0," and a weight that is known to be accurate should be attached to the belt. The weight should hang freely. A reading of that weight should be given accurately on the scale. If all conditions are met and the scale continues to show an incorrect reading for the known weight, the adjusting screw should be turned until the scale reads the appropriate weight.

When calibrating an ergometer that is braked by a lateral friction device, the ergometer is placed on 2 chairs so that the brake scale plate is vertical. After releasing the brake regulator knob on the handlebar, a known metric weight is hung on the brake arm using a wire S-hook. After loosening the fastening screw of the shock absorber at 1 end, the scale should read, in kiloponds, the exact amount of the weight attached to the brake arm. The pointer should always be read from directly above. If the scale does not read the weight accurately, the regulating nut should be turned. When the pointer indicates the same figure as the weight attached, the ergometer is calibrated correctly.

Mechanically braked ergometers can be delicate and may lose adjustment from frequent use or if they are transported. Before an ergometer is used, the chain should be checked for tightness and lubrication, and the braking surfaces of the flywheel should be free of any dirt that has gathered. A fine sandpaper pressed against the braking surface while pedaling the ergometer will smooth the surface.

Arm Ergometry

Mechanically braked arm ergometers should be manually calibrated routinely as recommended for bicycle ergometers. Electronically braked models require periodic calibration by experienced biomedical technicians as recommended by the specific equipment manufacturer.

Automated Blood Pressure Systems

Although manually determined blood pressure is recommended during exercise, several automated systems have been shown to provide reasonably accurate measurements of blood pressure during exercise.⁷³⁻⁷⁵ Calibration and maintenance procedures should be followed according to the manufacturer's specifications. Additionally, values obtained by the automated system should be compared periodically (monthly) with manual blood pressure measurements.

Gas Exchange Systems

The metabolic system should be calibrated immediately before each exercise test. This should include calibration of airflow and both the oxygen (O₂) and carbon dioxide (CO₂) analyzers. Gas analyzers and flow meters are prone to drift,

Table 9. Limits of Variation in Gas Exchange Variables Obtained by Repeated Study of the Same Subject at a Given Submaximal Workload

Variable	Variation
O ₂ uptake	±5.0%
CO ₂ output	±6.0%
\dot{V}_E	±5.5%
Respiratory exchange ratio	±3.0%
Heart rate	±4.5%
Systolic blood pressure	±6.0%
Diastolic blood pressure	±8.0%
Cardiac output	±6.5%

Data derived from Wasserman et al⁷⁹ and Jones.⁸⁰

which can lead to serious errors. Today, nearly all commercially available systems have convenient calibration procedures controlled by a microprocessor. Validation studies have been performed on a number of the computerized systems.^{76–78} Because ambient conditions affect the concentration of O₂ in the inspired air, it is necessary to account for temperature, barometric pressure, and humidity. Some presently available metabolic systems automatically quantify these conditions and make appropriate adjustments in the inspired O₂ concentration. If this feature is not available, these atmospheric conditions should be measured by an external device and input into the metabolic system. A copy of the calibration report should be printed before each test and should be attached to the test report. Valid interpretation of test results is possible only if calibration values are appropriate.

Modern metabolic systems use a wide variety of automated reports, data sampling techniques, calibration methods, and graphics. Although this has facilitated ease of use, it has also led to some confusion regarding which variables to consider and how the data should be expressed and interpreted. For example, many algorithms are available that automatically choose the ventilatory threshold or provide a diagnosis, and it is important that these be overread by a person experienced in cardiopulmonary exercise testing. In addition, differences in sampling (eg, breath-by-breath, an averaged number of breaths, or by time intervals such as 10, 15, or 30 seconds) can have a profound effect on test results. Because there is a need for consistency in this area that appropriately balances high precision but high variability (breath-by-breath) with imprecision but low variability (long sampling intervals), for routine clinical use, it is recommended that rolling 30-second averages be used that are printed frequently (eg, 10 seconds).

Gas exchange measurements are highly reproducible within a given subject if testing methods are consistent. One method often used to validate a system's performance is to test laboratory staff members at a matched submaximal workload on a periodic basis. It is recommended that several staff members participate in this process, each using a slightly different steady-state submaximal workload. Wasserman et al⁷⁹ suggest that oxygen consumption values should be within 5% to 10% of previous measurements after 3 minutes of steady-state submaximal exercise

at a given workload. Others^{80,81} have proposed acceptable limits of variation for oxygen uptake and for carbon dioxide production and ventilatory and hemodynamic data for a given steady-state workload (Table 9). The following specific calibration procedures should be performed to ensure that valid data are obtained:

1. Room air should read $20.93 \pm 0.03\%$ O₂ at 0% humidity; however, the precise fraction is dependent on humidity and should be adjusted accordingly. A calibration source containing 100% nitrogen should read 0% O₂. The analyzer should be checked further by simulating the fraction of expired O₂ (FEO₂) during the test, ie, approximately 16% O₂. The exercise laboratory should be well ventilated to ensure a representative fraction of inspired O₂; a fan is helpful for this purpose.
2. The CO₂ analyzer should read a room air fraction of $0.03 \pm 0.02\%$ and should not change when the 100% N₂ or 16% O₂ fractions are sampled from the calibration tanks. The CO₂ analyzer should be checked further by simulating the fraction of expired CO₂ (FECO₂) during exercise, ie, approximately 4% CO₂.
3. For breath-by-breath O₂ and CO₂ analyzers, it is also preferable to check the analyzer response time or delay. It is important that the system meet the specifications outlined by the manufacturer; this feature is available in most systems.
4. Measurement of ventilatory volume can now be easily achieved with 1 of several devices, including pneumotachometers, mass flow sensors, pitot tube flow meters, and turbine volume transducers. All can be validated before testing by ascertaining a stable baseline (0 L/min) and injecting a known volume (usually 3 or 4 L) from a syringe. It is preferable to perform several injections at different flow rates to ensure stability; the average error should be within $\pm 3\%$ of the known volume.³⁵

Appendix 1

Example of Informed Consent for Exercise Testing

To determine my cardiovascular response to exercise, I voluntarily agree to engage in an exercise test. The information obtained about my heart and circulation will be used to help my doctor understand more about any problems related to my heart and advise me about activities in which I may engage.

I understand that before I undergo the test, I will be evaluated either by a physician or by another member of the healthcare team in an attempt to determine if I have a condition indicating that I should not engage in this test.

The test I will undergo will be performed on a _____ (description), with gradually increasing effort until symptoms such as fatigue, shortness of breath, or chest discomfort may appear, indicating to me or to my physician that I should stop. I have been told that certain changes may occur during the test, including abnormal blood pressure, an abnormal electrocardiogram, and disorders of heart beat (too low, too fast, or ineffective).

Risks of this procedure are very low, but may include fainting, falling, irregularities of the heart beat, and, very rarely, heart attack or death (approximately 1 of these events may occur per 10,000 tests). Every effort will be made to minimize such risks through the preliminary examination and observations during testing. Professional staff and emergency equipment will be present during testing and emergency treatment will be available if it becomes necessary.

The information obtained will be treated as privileged and confidential and will not be released or revealed to any person without my expressed written consent. The information obtained, however, may be used for statistical or scientific purposes with my right of privacy retained.*

I have read the above and understand it, and my questions have been answered to my satisfaction.

Patient _____ Date _____

Physician Supervising the Test _____

Witness _____

Appendix 3

Sample Exercise Test Data Recording Form

--- Patient Information ---						Site: _____	
Name: _____ Age: ____ DOB: __/__/__ SSN: _____ TEST DATE: __/__/__						Physician : _____ Technician : _____	
Test PROTOCOL : _____ <input type="checkbox"/> (Indicate Time, TM Speed / Grade Below)				<input type="checkbox"/> - Exercise Echo <input type="checkbox"/> - Nuclear Imaging		Test Limiting Conditions : (e.g. Arthritis, Pulmonary, Orthopedic, CNS, Neuromuscular, Deconditioned, Obesity)	
----- EXERCISE TEST -----							CHEST PAIN: Type : 1=Definite/Typical ANGINA 2=Probable/Atypical ANGINA 3=Non-Cardiac Chest Pain Intensity : 1= (low) - 10 = (severe)
Exercise Time	Estimated METs	Speed / Grade	HR	Blood Pressure	PE (Borg)	CHEST PAIN Type /Intensity	Reason(s) for Test : <input type="checkbox"/> - CHEST PAIN was main reason for test <input type="checkbox"/> - CHEST PAIN/ Angina <input type="checkbox"/> - Signs/symptoms and/or risk factors for CAD <input type="checkbox"/> - Recent Post MI (<6 mo) <input type="checkbox"/> - Exercise Capacity <input type="checkbox"/> - Decreased Exercise Capacity <input type="checkbox"/> - Health Maintenance <input type="checkbox"/> - Disability Evaluation <input type="checkbox"/> - Pre-Operative <input type="checkbox"/> - Syncope <input type="checkbox"/> - Dyspnea on Exertion <input type="checkbox"/> - Arrhythmias <input type="checkbox"/> - Post Cardiac surgery <input type="checkbox"/> - Post Revascularization Others: _____ Reason(s) to END TEST <input type="checkbox"/> - Normal endpoint: Reached target/fatigue <input type="checkbox"/> - Angina was main reason to end test <input type="checkbox"/> - Angina <input type="checkbox"/> - Other Chest Pain <input type="checkbox"/> - Patient Uncooperative <input type="checkbox"/> - Dyspnea <input type="checkbox"/> - Leg Fatigue <input type="checkbox"/> - Claudication <input type="checkbox"/> - Other Leg Pain <input type="checkbox"/> - Arm Pain <input type="checkbox"/> - Jaw Pain <input type="checkbox"/> - CNS Symptoms <input type="checkbox"/> - Sub-MAX Target <input type="checkbox"/> - ST Changes <input type="checkbox"/> - Dysrhythmias <input type="checkbox"/> - Technical Difficulties Others: _____
Supine :	---0---	---0---	/	---0---			
Standing :	---0---	---0---	/	---0---			
: / /							
: / /							
: / /							
: / /							
: / /							
: / /							
: / /							
: / /							
: / /							
: / /							
: / /							
----- MAX EXERCISE -----							
TOTAL							
: / /							
----- RECOVERY -----							
<= 1 min :	---0---	---0---	/	---0---			
2 min :	---0---	---0---	/	---0---			
5 min :	---0---	---0---	/	---0---			
8 min :	---0---	---0---	/	---0---			
Gas Analysis/Spirometry Results: FEV ₁ : _____ FVC : _____ Measured METs: _____ Peak VO ₂ (ml/kg/min): _____							
NOTES:							Exercise Time Chest Pain Resolved: _____ : _____ mm ss

Disclosures

Writing Group Disclosures

Writing Group Member	Employment	Research Grant	Other Research Support	Speakers' Bureau/Honoraria	Expert Witness	Ownership Interest	Consultant/Advisory Board	Other
Jonathan Myers	Palo Alto Veterans Administration Health Care Service	NIH†	None	None	None	None	None	None
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Barry Franklin	William Beaumont Hospital	None	None	Receives modest honoraria throughout the year (generally from hospitals, medical centers, or cardiac rehabilitation associations) for selected "invited presentations"*	None	None	Eli Lilly*; Smart Balance*	None
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Kyle McInnis	University of Massachusetts	None	None	None	None	None	None	None
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This table represents the relationships of writing group members that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all members of the writing group are required to complete and submit. A relationship is considered to be "significant" if (1) the person receives \$10 000 or more during any 12-month period, or 5% or more of the person's gross income; or (2) the person owns 5% or more of the voting stock or share of the entity, or owns \$10 000 or more of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

*Modest.

†Significant.

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This table represents the relationships of reviewers that may be perceived as actual or reasonably perceived conflicts of interest as reported on the Disclosure Questionnaire, which all reviewers are required to complete and submit. A relationship is considered to be "significant" if (1) the person receives \$10 000 or more during any 12-month period, or 5% or more of the person's gross income; or (2) the person owns 5% or more of the voting stock or share of the entity, or owns \$10 000 or more of the fair market value of the entity. A relationship is considered to be "modest" if it is less than "significant" under the preceding definition.

*Modest.

References

1. Washington RL, Bricker JT, Alpert BS, Daniels SR, Deckelbaum RJ, Fisher EA, Gidding SS, Isabel-Jones J, Kavey RE, Marx GR. Guidelines for exercise testing in the pediatric age group: from the Committee on Atherosclerosis and Hypertension in Children, Council on Cardiovascular Disease in the Young, the American Heart Association. *Circulation*. 1994;90:2166–2179.
2. Pina IL, Balady GJ, Hanson P, Labovitz AJ, Madonna DW, Myers J. Guidelines for clinical exercise testing laboratories: a statement for healthcare professionals from the Committee on Exercise and Cardiac Rehabilitation, American Heart Association. *Circulation*. 1995;91:912–921.
3. Gibbons RJ, Balady GJ, Timothy BJ, Chaitman BR, Fletcher GF, Froelicher VF, Mark DB, McCallister BD, Mooss AN, O'Reilly MG, Winters WL, Gibbons RJ, Antman EM, Alpert JS, Faxon DP, Fuster V, Gregoratos G,

- Hiratzka LF, Jacobs AK, Russell RO, Smith SC. ACC/AHA 2002 guideline update for exercise testing: summary article: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Committee to Update the 1997 Exercise Testing Guidelines) [published correction appears in *J Am Coll Cardiol*. 2006;48:1731]. *J Am Coll Cardiol*. 2002;40:1531–1540.
4. Fletcher GF, Balady GJ, Amsterdam EA, Chaitman B, Eckel R, Fleg J, Froelicher VF, Leon AS, Piña IL, Rodney R, Simons-Morton DA, Williams MA, Bazzarre T. Exercise standards for testing and training: a statement for healthcare professionals from the American Heart Association. *Circulation*. 2001;104:1694–1740.
 5. Rodgers GP, Ayanian JZ, Balady G, Beasley JW, Brown KA, Gervino EV, Paridon S, Quinones M, Schlant RC, Winters WL Jr, Achord JL, Boone AW, Hirshfeld JW Jr, Lorell BH, Rodgers GP, Tracy CM, Weitz HH. American College of Cardiology/American Heart Association clinical competence statement on stress testing: a report of the American College of Cardiology/American Heart Association/American College of Physicians–American Society of Internal Medicine Task Force on Clinical Competence. *J Am Coll Cardiol*. 2000;36:1441–1453.
 6. Arena R, Myers J, Williams MA, Gulati M, Kligfield P, Balady GJ, Collins E, Fletcher G. Assessment of functional capacity in clinical and research settings: a scientific statement from the American Heart Association Committee on Exercise, Rehabilitation, and Prevention of the Council on Clinical Cardiology and the Council on Cardiovascular Nursing. *Circulation*. 2007;116:329–343.
 7. Borg GAV. *Borg's Scales of Perceived Exertion*. Champaign, Ill: Human Kinetics; 1999.
 8. American College of Sports Medicine. *ACSM's Guidelines for Exercise Testing and Prescription*. 7th ed. Philadelphia, Pa: Lippincott Williams & Wilkins; 2006.
 9. Myers JN. Perception of chest pain during exercise testing in patients with coronary artery disease. *Med Sci Sports Exerc*. 1994;26:1082–1086.
 10. Mahler DA, Horowitz MB. Clinical evaluation of exertional dyspnea. *Clin Chest Med*. 1994;15:259–269.
 11. Kligfield P, Gettes LS, Bailey JJ, Childers R, Deal BJ, Hancock EW, van Herpen G, Kors JA, Macfarlane P, Mirvis DM, Pahlm O, Rautaharju P, Wagner GS. Recommendations for the standardization and interpretation of the electrocardiogram: part I: the electrocardiogram and its technology: a scientific statement from the American Heart Association Electrocardiography and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation; and the Heart Rhythm Society. *Circulation*. 2007;115:1306–1324.
 12. Froelicher VF, Myers J. *Exercise and the Heart*. 5th ed. Philadelphia, Pa: WB Saunders; 2006.
 13. Perloff D, Grim C, Flack J, Frohlich ED, Hill M, McDonald M, Morgenstern BZ. Human blood pressure determination by sphygmomanometry. *Circulation*. 1993;88(pt 1):2460–2470.
 14. Jones DW, Appel LJ, Sheps SG, Roccella EJ, Lenfant C. Measuring blood pressure accurately: new and persistent challenges. *JAMA*. 2003;289:1027–1030.
 15. Myers J. *Essentials of Cardiopulmonary Exercise Testing*. Champaign, Ill: Human Kinetics; 1996:59–81.
 16. Hambrecht R, Schuler GC, Muth T, Grunze MF, Marburger CT, Niebauer J, Methfessel SM, Kübler W. Greater diagnostic sensitivity of treadmill versus cycle exercise testing of asymptomatic men with coronary artery disease. *Am J Cardiol*. 1992;70:141–146.
 17. Balady GJ, Weiner DA, Rose L, Ryan TJ. Physiologic responses to arm ergometry exercise relative to age and gender. *J Am Coll Cardiol*. 1990;16:130–135.
 18. Hagan RD, Gettman LR, Upton SJ, Duncan JJ, Cummings JM. Cardio-respiratory responses to arm, leg, and combined arm and leg work on an air-braked ergometer. *J Cardiac Rehabil*. 1983;3:689–695.
 19. Glaser RM. Arm exercise training for wheelchair users. *Med Sci Sports Exerc*. 1989;21(suppl):S149–S157.
 20. Secher NH, Volianitis S. Are the arms and legs in competition for cardiac output? *Med Sci Sports Exerc*. 2006;38:1797–1803.
 21. Pendergast DR. Cardiovascular, respiratory, and metabolic responses to upper body exercise. *Med Sci Sports Exerc*. 1989;21(suppl):S121–S125.
 22. Balady GJ, Weiner DA, Rothendler JA, Ryan TJ. Arm exercise-thallium imaging testing for the detection of coronary artery disease. *J Am Coll Cardiol*. 1987;9:84–88.
 23. Sullivan M, Genter F, Savvides M, Roberts M, Myers J, Froelicher V. The reproducibility of hemodynamic, electrocardiographic, and gas exchange data during treadmill exercise in patients with stable angina pectoris. *Chest*. 1984;86:375–382.
 24. Marburger CT, Brubaker PH, Pollock WE, Morgan TM, Kitzman DW. Reproducibility of cardiopulmonary exercise testing in elderly patients with congestive heart failure. *Am J Cardiol*. 1998;82:905–909.
 25. Arena R, Myers J, Aslam SS, Varughese EB, Peberdy MA. Peak VO_2 and VE/VCO_2 slope in patients with heart failure: a prognostic comparison. *Am Heart J*. 2004;147:354–360.
 26. Koike A, Itoh H, Kato M, Sawada H, Aizawa T, Fu LT, Watanabe H. Prognostic power of ventilatory responses during submaximal exercise in patients with chronic heart disease. *Chest*. 2002;121:1581–1588.
 27. Reindl I, Wemecke KD, Opitz C, Wensel R, König D, Dengler T, Schimke I, Kleber FX. Impaired ventilatory efficiency in chronic heart failure: possible role of pulmonary vasoconstriction. *Am Heart J*. 1998;136:778–785.
 28. Matsumoto A, Itoh H, Eto Y, Kobayashi T, Kato M, Omata M, Watanabe H, Kato K, Momomura S. End-tidal CO_2 pressure decreases during exercise in cardiac patients: association with severity of heart failure and cardiac output reserve. *J Am Coll Cardiol*. 2000;36:242–249.
 29. Arena R, Peberdy MA, Myers J, Guazzi M, Tevald M. Prognostic value of resting end-tidal carbon dioxide in patients with heart failure. *Int J Cardiol*. 2006;109:351–358.
 30. Francis DP, Shamim W, Davies LC, Piepoli MF, Ponikowski P, Anker SD, Coats AJ. Cardiopulmonary exercise testing for prognosis in chronic heart failure: continuous and independent prognostic value from VE/VCO_2 slope and peak VO_2 . *Eur Heart J*. 2000;21:154–161.
 31. Myers J, Gullestad L, Vagelos R, Do D, Bellin D, Ross H, Fowler MB. Cardiopulmonary exercise testing and prognosis in severe heart failure: 14 mL/kg/min revisited. *Am Heart J*. 2000;139(pt 1):78–84.
 32. Guazzi M, Palermo P, Pontone G, Susini F, Agostoni P. Synergistic efficacy of enalapril and losartan on exercise performance and oxygen consumption at peak exercise in congestive heart failure. *Am J Cardiol*. 1999;84:1038–1043.
 33. Malfatto G, Facchini M, Branzi G, Brambilla R, Friatianni G, Tortorici E, Balla E, Perego GB. Reverse ventricular remodeling and improved functional capacity after ventricular resynchronization in advanced heart failure. *Ital Heart J*. 2005;6:578–583.
 34. Myers J, Dziekan G, Goebbels U, Dubach P. Influence of high-intensity exercise training on the ventilatory response to exercise in patients with reduced ventricular function. *Med Sci Sports Exerc*. 1999;31:929–937.
 35. American Thoracic Society/American College of Chest Physicians. ATS/ACCP statement on cardiopulmonary exercise testing [published correction appears in *Am J Respir Crit Care Med*. 2003;167:1451–1452]. *Am J Respir Crit Care Med*. 2003;167:211–277.
 36. Task Force of the Italian Working Group on Cardiac Rehabilitation Prevention; Working Group on Cardiac Rehabilitation and Exercise Physiology of the European Society of Cardiology; Piepoli MF, Corrà U, Agostoni PG, Belardinelli R, Cohen-Solal A, Hambrecht R, Vanhees L. Statement on cardiopulmonary exercise testing in chronic heart failure due to left ventricular dysfunction: recommendations for performance and interpretation, part I: definition of cardiopulmonary exercise testing parameters for appropriate use in chronic heart failure. *Eur J Cardiovasc Prev Rehabil*. 2006;13:150–164.
 37. Task Force of the Italian Working Group on Cardiac Rehabilitation and Prevention (Gruppo Italiano di Cardiologia Riabilitativa e Prevenzione, GICR); Working Group on Cardiac Rehabilitation and Exercise Physiology of the European Society of Cardiology; Piepoli MF, Corrà U, Agostoni PG, Belardinelli R, Cohen-Solal A, Hambrecht R, Vanhees L. Statement on cardiopulmonary exercise testing in chronic heart failure due to left ventricular dysfunction: recommendations for performance and interpretation, part II: how to perform cardiopulmonary exercise testing in chronic heart failure. *Eur J Cardiovasc Prev Rehabil*. 2006;13:300–311.
 38. Task Force of the Italian Working Group on Cardiac Rehabilitation and Prevention (Gruppo Italiano di Cardiologia Riabilitativa e Prevenzione, GICR); Working Group on Cardiac Rehabilitation and Exercise Physiology of the European Society of Cardiology; Piepoli MF, Corrà U, Agostoni PG, Belardinelli R, Cohen-Solal A, Hambrecht R, Vanhees L. Statement on cardiopulmonary exercise testing in chronic heart failure due to left ventricular dysfunction: recommendations for performance and interpretation, part III: interpretation of cardiopulmonary exercise testing in chronic heart failure and future applications. *Eur J Cardiovasc Prev Rehabil*. 2006;13:485–494.
 39. ERS Task Force; Palange P, Ward SA, Carlsen KH, Casaburi R, Gallagher CG, Gosselink R, O'Donnell DE, Puente-Maestu L, Schols AM, Singh S, Whipp BJ. Recommendations on the use of exercise testing in clinical practice. *Eur Respir J*. 2007;29:185–209.
 40. Klocke FJ, Baird MG, Lorell BH, Bateman TM, Messer JV, Berman DS, O'Gara PT, Carabello BA, Russell RO Jr, Cerqueira MD, St John Sutton MG, DeMaria AN, Udelson JE, Kennedy JW, Verani MS, Williams KA,

- Antman EM, Smith SC Jr, Alpert JS, Gregoratos G, Anderson JL, Hiratzka LF, Faxon DP, Hunt SA, Fuster V, Jacobs AK, Gibbons RJ, Russell RO. ACC/AHA/ASNC guidelines for the clinical use of cardiac radionuclide imaging: executive summary: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (ACC/AHA/ASNC Committee to Revise the 1995 Guidelines for the Clinical Use of Cardiac Radionuclide Imaging). *Circulation*. 2003;108:1404–1418.
41. Cheitlin MD, Armstrong WF, Aurigemma GP, Beller GA, Bierman FZ, Davis JL, Douglas PS, Faxon DP, Gillam LD, Kimball TR, Kussmaul WG, Pearlman AS, Philbrick JT, Rakowski H, Thys DM, Antman EM, Smith SC Jr, Alpert JS, Gregoratos G, Anderson JL, Hiratzka LF, Hunt SA, Fuster V, Jacobs AK, Gibbons RJ, Russell RO. ACC/AHA/ASE 2003 guideline update for the clinical application of echocardiography: summary article: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (ACC/AHA/ASE Committee to Update the 1997 Guidelines for the Clinical Application of Echocardiography). *Circulation*. 2003;108:1146–1162.
 42. Foote RS, Pearlman JD, Siegel AH, Yeo KT. Detection of exercise-induced ischemia by changes in B-type natriuretic peptides. *J Am Coll Cardiol*. 2004;44:1980–1987.
 43. Yeo KT, Lee HK, Wong KC, Foote RS. Can exercise-induced changes in B-type natriuretic peptides be used to detect cardiac ischemia? *J Card Fail*. 2005;11:S59–S64.
 44. Sabatine MS, Morrow DA, de Lemos JA, Omland T, Desai MY, Tanasijevic M, Hall C, McCabe CH, Braunwald E. Acute changes in circulating natriuretic peptide levels in relation to myocardial ischemia. *J Am Coll Cardiol*. 2004;44:1988–1995.
 45. American College of Sports Medicine/American Heart Association Joint Position Statement. American College of Sports Medicine Position Statement and American Heart Association: recommendations for cardiovascular screening, staffing, and emergency policies at health/fitness facilities. *Med Sci Sports Exerc*. 1998;30:1009–1018.
 46. American College of Sports Medicine and American Heart Association joint position statement: automated external defibrillators in health/fitness facilities. *Med Sci Sports Exerc*. 2002;34:561–564.
 47. Ali B, Zafari AM. Narrative review: cardiopulmonary resuscitation and emergency cardiovascular care: review of the current guidelines [published correction appears in *Ann Intern Med*. 2007;147:592]. *Ann Intern Med*. 2007;147:171–179.
 48. Sicari R. Anti-ischemic therapy and stress testing: pathophysiologic, diagnostic and prognostic implications. *Cardiovasc Ultrasound*. 2004;2:14.
 49. Hlatky MA, Boineau RE, Higginbotham MB, Lee KL, Mark DB, Califf RM, Cobb FR, Pryor DB. A brief self-administered questionnaire to determine functional capacity (the Duke Activity Status Index). *Am J Cardiol*. 1989;64:651–654.
 50. Myers J, Bader D, Madhavan R, Froelicher V. Validation of a specific activity questionnaire to estimate exercise tolerance in patients referred for exercise testing. *Am Heart J*. 2001;142:1041–1046.
 51. Abe K, Tsuda M, Hayashi H, Hirai M, Sato A, Tsuzuki J, Saito H. Diagnostic usefulness of postexercise systolic blood pressure response for detection of coronary artery disease in patients with electrocardiographic left ventricular hypertrophy. *Am J Cardiol*. 1995;76:892–895.
 52. Michaelides AP, Fourlas CA, Giannopoulos N, Aggeli K, Andrikopoulos GK, Tsioufis K, Massias SS, Stefanadis CI. Significance of QRS duration changes in the evaluation of ST-segment depression presenting exclusively during the postexercise recovery period. *Ann Noninvasive Electrocardiol*. 2006;11:241–246.
 53. Pitsavos CH, Chrysohou C, Panagiotakos DB, Kokkinos P, Skoumas J, Papaioannou I, Michaelides AP, Singh S, Stefanadis CI. Exercise capacity and heart rate recovery as predictors of coronary heart disease events, in patients with heterozygous familial hypercholesterolemia. *Atherosclerosis*. 2004;173:347–350.
 54. Bjurö T, Gullestad L, Endresen K, Nordlander M, Malm A, Höglund L, Wahlqvist I, Pernow J. Evaluation of ST-segment changes during and after maximal exercise tests in one-, two- and three-vessel coronary artery disease. *Scand Cardiovasc J*. 2004;38:270–277.
 55. Gullestad L, Jorgensen B, Bjuro T, Pernow J, Lundberg JM, Dota CD, Hall C, Simonsen S, Ablad B. Postexercise ischemia is associated with increased neuropeptide Y in patients with coronary artery disease. *Circulation*. 2000;102:987–993.
 56. Myers J, Voodi L, Umann T, Froelicher VF. A survey of exercise testing: methods, utilization, interpretation, and safety in the VAHCS. *J Cardiopulm Rehabil Prev*. 2000;20:251–258.
 57. Gordon NF, Kohl HW. Exercise testing and sudden cardiac death. *J Cardiopulm Rehabil*. 1993;13:381–386.
 58. Stuart RJ Jr, Ellestad MH. National survey of exercise stress testing facilities. *Chest*. 1980;77:94–97.
 59. Ellestad MH, Blomqvist CG, Naughton JP; American Heart Association Subcommittee on Rehabilitation Target Activity Group. Standards for adult exercise testing laboratories. *Circulation*. 1979;59:421A–430A.
 60. Franklin BA, Gordon S, Timms GC, O'Neill WW. Is direct physician supervision of exercise stress testing routinely necessary? *Chest*. 1997;111:262–265.
 61. Cahalin LP, Blessey RL, Kummer D, Simard M. The safety of exercise testing performed independently by physical therapists. *J Cardiopulm Rehabil Prev*. 1987;7:269–276.
 62. Lem V, Krivokapich J, Child JS. A nurse-supervised exercise stress testing laboratory. *Heart Lung*. 1985;14:280–284.
 63. De Busk RF. Exercise test supervision: time for a reassessment. *Exerc Stand Malpractice Rep*. 1988;2:65–70.
 64. Knight JA, Laubach CA Jr, Butcher RJ, Menapace FJ. Supervision of clinical exercise testing by exercise physiologists. *Am J Cardiol*. 1995;75:390–391.
 65. Davis G, Ortloff S, Reed A, Worthington G, Roberts D. Evaluation of technician supervised treadmill exercise testing in a cardiac chest pain clinic. *Heart*. 1998;79:613–615.
 66. Muir DF, Jummun M, Stewart DJ, Clark AL. Diagnostic accuracy of technician supervised and reported exercise tolerance tests. *Heart*. 2002;87:381–382.
 67. Madriago E, Baker L, Amsterdam EA. Supervision and interpretation of exercise treadmill tests by physician assistants. *Crit Pathw Cardiol*. 2005;4:182–184.
 68. Chinnaiyan KM, Trivax J, Franklin BA, Williamson B, Kahn JK. Stress testing in patients with implantable cardioverter-defibrillators: a preliminary report. *Prev Cardiol*. 2007;10:92–95.
 69. Kane GC, Hepinstall MJ, Kidd GM, Kuehl CA, Murphy AT, Nelson JM, Schneider L, Stussy VL, Warnsbecker JA, Miller FA Jr, Pellikka PA, McCully RB. Safety of stress echocardiography supervised by registered nurses: results of a 2-year audit of 15,404 patients. *J Am Soc Echocardiogr*. 2008;21:337–341.
 70. Squires RW, Allison TG, Johnson BD, Gau GT. Non-physician supervision of cardiopulmonary exercise testing in chronic heart failure: safety and results of a preliminary investigation. *J Cardiopulm Rehabil*. 1999;19:249–253.
 - 70a. Gibbons RJ, Balady GJ, Beasley JW, Bricker JT, Duvernoy WFC, Froelicher VF, Mark DB, Marwick TH, McAllister BD, Thompson PD, Winters WL, Yanowitz FG. ACC/AHA guidelines for exercise testing: a report of the American College of Cardiology/American Heart Association Task Force on Practice Guidelines (Committee on Exercise Testing). *J Am Coll Cardiol*. 1997;30:260–315.
 71. Maier E, Jensen L, Sonnenberg B, Archer S. Interpretation of exercise stress test recordings: concordance between nurse practitioner and cardiologist. *Heart Lung*. 2008;37:144–152.
 72. Herbert DL, Herbert WG, Collum JJ. Legal considerations. In: Ehrman JK, Gordon PM, Visich PS, Keteyian SJ, eds. *Clinical Exercise Physiology*. Champaign, Ill: Human Kinetics; 2003:25–40.
 73. Griffin SE, Robergs RA, Heyward VH. Blood pressure measurement during exercise: a review. *Med Sci Sports Exerc*. 1997;29:149–159.
 74. Cameron JD, Stevenson I, Reed E, McGrath BP, Dart AM, Kingwell BA. Accuracy of automated auscultatory blood pressure measurement during supine exercise and treadmill stress electrocardiogram-testing. *Blood Press Monit*. 2004;9:269–275.
 75. MacRae HS, Allen PJ. Automated blood pressure measurement at rest and during exercise: evaluation of the motion tolerant CardioDyne NBP 2000. *Med Sci Sports Exerc*. 1998;30:328–331.
 76. Crouter SE Antczak A, Hudak JR, Della Valle DM, Haas JD. Accuracy and reliability of the ParvoMedics TrueOne 2400 and MedGraphics VO2000 metabolic systems. *Eur J Appl Physiol*. 2006;98:139–151.
 77. Carter J, Jeukendrup AE. Validity and reliability of three commercially available breath-by-breath respiratory systems. *Eur J Appl Physiol*. 2002; 86:435–441.
 78. Foss Ø, Hallén J. Validity and stability of a computerized metabolic system with mixing chamber. *Int J Sports Med*. 2005;26:569–575.
 79. Wasserman K, Hansen JE, Sue DY, Stringer W, Whipp B. Clinical exercise testing. In: Wasserman K, ed. *Principles of Exercise Testing and Interpretation*. 4th ed. Philadelphia, Pa: Lippincott Williams & Wilkins; 2005:133–159.
 80. Jones N. Quality control in exercise studies. In: Jones N. *Clinical Exercise Testing*. 4th ed. Philadelphia, Pa: WB Saunders; 1997:164–166.
 81. Wilmore JH, Skinner PR, Turley KR, Gagnon J, Daw EW, Leon AS, Rao DC, Skinner JS, Bouchard C. Reproducibility of cardiovascular, respiratory, and metabolic responses to submaximal exercise: the HERITAGE Family Study. *Med Sci Sports Exerc*. 1998;30:259–265.