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AHA Scientific Statement

Clinical Stress Testing in the Pediatric Age Group

A Statement From the American Heart Association Council on Cardiovascular Disease in the Young, Committee on Atherosclerosis, Hypertension, and Obesity in Youth

Stephen M. Paridon, MD; Bruce S. Alpert, MD, FAHA; Steven R. Boas, MD; Marco E. Cabrera, PhD; Laura L. Caldarera, MA; Stephen R. Daniels, MD, PhD, FAHA; Thomas R. Kimball, MD; Timothy K. Knilans, MD; Patricia A. Nixon, PhD; Jonathan Rhodes, MD; Angela T. Yetman, MD

Abstract**—**This statement is an updated report of the American Heart Association's previous publications on exercise in children. In this statement, exercise laboratory requirements for environment, equipment, staffing, and procedures are presented. Indications and contraindications to stress testing are discussed, as are types of testing protocols and the use of pharmacological stress protocols. Current stress laboratory practices are reviewed on the basis of a survey of pediatric cardiology training programs. **(*Circulation*. 2006;113:1905-1920.)**

Key Words: AHA Scientific Statements ■ pediatrics ■ stress test ■ exercise test

This statement is an updated report of previous American Heart Association (AHA) publications on exercise testing in children. This statement is intended for physicians, nurses, exercise physiologists/specialists, physical educators, exercise technologists, and other healthcare professionals involved in exercise testing or training of children and adolescents. This report is intended to supplement and update the previous AHA publications on exercise testing in children.[1–3]

Over the past decade, the role of the pediatric exercise physiology laboratory has expanded significantly. In addition to children with congenital and acquired heart disease, patients with pulmonary, gastrointestinal, metabolic, and other organ system disorders are routinely undergoing evaluation. The use of stress echocardiography, nuclear imaging, and magnetic resonance imaging is becoming more common in the pediatric population.[4–9] For these reasons, considerations of testing protocol and equipment needs for these populations are included in this report. The use of pharmacological agents to stress the cardiovascular system has also become common in situations in which performance of a conventional exercise test is impractical.[4,7–9] Information about pharmacological testing is also included in this report. The term "Stress Testing" rather than "Exercise Testing" has been chosen in the title of the present document to reflect this broadening of testing modalities.

I. Physical Environment

The exercise physiology laboratory should provide an ideal environment for vigorous exercise. This requires adequate space and climate control. The laboratory must be large enough to accommodate the treadmill and/or cycle ergometer, ECG machine, metabolic cart, and patient examination table and still be able to provide sufficient room on both sides of the ergometer for emergency equipment should it be needed. Approximately 500 sq ft is usually adequate. With the use of multiple ergometers and testing stations, the space allocated must increase proportionally.[10] It is also preferable to have a space at the back of the room for a parent to sit during the test. Temperature should be maintained in the range of 20°C (68°F) to 24°C (75°F) with a relative humidity of between 50% and 60%. Lighting throughout the laboratory must be adequate to allow complete viewing of the patient and equipment.[10,11]

Laboratory Equipment

The pediatric exercise physiology laboratory must be equipped with age- and size-appropriate ergometers, emergency equipment, and measurement devices (such as appro-

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Exercise Test Information

A Metabolic Exercise Test helps your doctor find out how well your child's heart, lungs, and muscles work during exercise. The test can also show if there is a lack of blood supply to the heart as your child does work, and helps the doctor know the kind and level of activity that's right for your child.

During the test, your child will be hooked up to equipment to monitor his or her heart and blood pressure, and may also be asked to breathe into a mouthpiece before, during, and after exercise. Your child will walk slowly in place on the treadmill. Every few minutes, the speed of the treadmill will get faster and the treadmill will tilt so it will feel like your child is walking up a hill. Your child can stop the test at any time if he/she needs to. Most children walk for 10 to 15 minutes; however, there is no set time limit for the test. Your child will only be asked to work to the best of his/her abilities.

As your child walks on the treadmill, several things will be monitored and recorded for the physician. These include:

- Heart rate and heart rhythm
- Blood pressure
- Breathing
- How tired your child feels

For the test, your child should wear comfortable clothing that he/she can exercise in. Shorts or sweatpants and a T-shirt are recommended. Athletic shoes should be worn (no open-toed shoes or sandals, please). Your child can eat a light meal or snack before the test.

Figure 1. A sample of the form used to explain an exercise test to parents and patients. See text for discussion.

priately sized blood pressure cuffs, pediatric mouthpieces, and pediatric face masks). A treadmill should have appropriate-height handrails (both sides and front). Most treadmill manufacturers have commercially available attachments for this purpose. Cycle ergometers have adjustable seat height so that the child can reach the pedals and have an ≈10° to 15° angle of flexion at the knee when the leg is extended. It may be necessary to use blocks to increase the height of the pedals for smaller children, although it is always better to use ergometers with adjustable leg cranks and handlebars. A fully stocked emergency resuscitation cart should be present in the laboratory during testing. Additional safety equipment such as oxygen and suction should be present in the laboratory during all testing. See the section on equipment requirements for a detailed discussion.

Pretest Procedures

Before the arrival of the patient for testing, it is helpful to provide the patient and family with written information about the test as well as pretest guidelines with regard to diet and clothing. Patients do not have to be fasting for a standard cardiopulmonary exercise test. However, they are cautioned not to consume caffeine on the day of the test (including caffeinated soda) or eat a heavy meal within 2 to 3 hours of the test. Patients are instructed to wear or bring comfortable exercise clothing, preferably shorts, T-shirt, and athletic shoes. The pretest information can be mailed to the family with an appointment reminder and instructions to come to the laboratory well rested (Figure 1).

When the patient arrives at the exercise laboratory for testing, the testing procedure should be explained again to the child and the parent in terms that they can both understand. For standard cardiopulmonary exercise testing, children should be reassured that the test does not hurt and is usually even fun. The child and parent should then be given the opportunity to have all questions about the test answered.[11] Written informed consent is often obtained before the exercise test, and the patient should be told that he or she can terminate the test at any time even though he or she will be encouraged to continue to volitional fatigue and that the time he or she will be exercising is usually 10 to 15 minutes. The consent form used may be specific for the exercise physiology laboratory and may be similar to the sample pretest patient information form shown here (Figure 1). It may also be a hospital-wide standard consent form filled out specifically for exercise testing. The use and type of each form will vary according to the individual institution's requirements but should meet the standards of meaningful informed consent (see section on consent/assent below). Verbal assent should be obtained from the child if over the age of 7 or 8 years.

In preparation for the test, the patient is fitted with 10 electrodes so that a continuous 12-lead ECG tracing can be obtained during testing. The skin should be cleansed with alcohol, with care taken to assure small children that this does not indicate they will be getting an injection because many children associate alcohol swabs with needles. The skin should be abraded gently with ECG skin preparation paper or rough gauze. Some clinicians believe that commercially available "drills" and electrode placement guns are useful. Electrode placement should be in a modified version of the Mason-Likar placement, with the arm leads at the lateral and superior corners of the sternum and the leg electrodes near the right and left inferior rib margins between the midclavicular and anterior axillary lines. In patients undergoing exercise echocardiography, the position of the electrodes may be modified slightly to permit access to adequate echocardiographic windows. Likewise, lead position may need to be modified to accommodate breast tissue in adolescent females, and chest hair removal may be needed in adolescent males. The lead wires should then be attached to the electrodes and the patient cable and lead-wire box fitted snugly around the child's waist. A stress test vest or net shirt helps to keep the electrodes and wires firmly in place when the child is exercising. Appropriately sized blood pressure cuff and pulse oximeter sensor (if used) should be placed at this time.[11]

Before exercise, the patient should be given the opportunity to familiarize himself or herself with the breathing apparatus (airtight mouthpiece or mask) if a metabolic or pulmonary stress test is to be administered. With the recent improvements in face mask design for ventilatory and gas exchange measurements, it is more comfortable for the patient to have the freedom to breathe through either the nose or mouth. Breathing with a face mask is more natural and prevents coughing and drying of the airways. At the onset of exercise, patients should be given a warm-up period consisting of low or no workload to acclimate the patient and to collect baseline data. (See protocols for more detailed discussion.) Before the exercise test, the staff should also familiarize themselves with the patient's medical history so that they may anticipate abnormalities that may be encountered during

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the test and identify the clinical questions that need to be addressed by the test.

Laboratory Staffing

A physician trained in exercise testing and exercise physiology should have the primary oversight responsibility for the laboratory and testing. The American College of Cardiology and the AHA have recently published a statement on clinical competency for stress testing. This statement includes recommendations about the clinical training and competency requirements for physicians supervising pediatric exercise and stress testing.[12] These recommendations should be considered when a physician's competence to supervise a pediatric exercise laboratory is evaluated.

The director of the exercise laboratory may be either a physician responsible for the laboratory or a nonphysician trained in pediatric exercise physiology and testing. Ideally, a nonphysician director should have training in exercise physiology at least at a master's degree level. The director's responsibilities include ensuring that (1) all laboratory personnel are thoroughly trained in testing and emergency procedures; (2) all equipment is working properly and is properly maintained; (3) appropriate testing procedures are used on the basis of the patient's diagnosis and the information desired from the exercise test; and (4) results of the stress testing are conveyed in a reliable and timely manner to both the referring physician and family.[1,12]

An exercise test may be conducted by laboratory personnel who have been properly screened, are familiar with pediatric pathophysiological responses to exercise testing, and have expertise in pediatric emergency procedures. At least 2 properly trained persons are needed to perform an exercise test. At least one of these should be trained in pediatric advanced life support, and standard pediatric cardiopulmonary resuscitative equipment should be immediately available during all testing.[12]

For all diagnostic testing, a physician should be immediately available. Physicians may need to be present and/or supervise testing depending on the risk to the patient, the expertise of the laboratory personnel, and the complexity of the clinical question being addressed. Most low-risk testing (see subsequent section) may be done without direct in-laboratory physician supervision. Higher-risk studies should have direct supervision. Individual patient risks should always be taken into consideration when the decision is made about physician supervision. The physician's role and personnel needed for pharmacological stress testing will be discussed in the protocol sections.

II. Informed Consent

In the most recent AHA statement on pediatric exercise testing,[1] it was suggested that most exercise testing laboratories have a meaningful written consent for the procedure. In the survey conducted for this statement, of the centers responding, only approximately one half required written informed consent before the procedure (see below).

It is recognized that different institutions have different approaches to the process of informing patients and their families about medical procedures. There may be differences in the law from state to state. Nevertheless, it is vitally important that young patients and their parents know what to expect when they are involved in exercise testing. This information about what will be done, why the test is needed, and which aspects of the test may result in discomfort or risk is necessary to obtain the best test results. For some patients, the risk of exercise may be higher. For these patients, a careful explanation of the risks involved and the precautions taken to avoid excess risk or to deal with expected or unexpected medical complications is important. It may also be helpful to document that this exchange of information has occurred, either in the patient's medical record or with an informed consent document. The personnel of the laboratory should respect the right of the family to be informed about the test. A discussion of how or why the test might be terminated, including at the request of the patient, should also occur before the test. The patient's right to terminate the test should be respected.

III. Equipment Requirements

A pediatric exercise laboratory should be able to perform a spectrum of testing on children with a wide variety of medical conditions. This will usually require at least a treadmill and a cycle ergometer. In addition, equipment to measure physiological responses to exercise such as heart rate, blood pressure, oxygen saturation, and expired gases is usually required. Equipment for more specialized testing such as pharmacological stress testing and echocardiographic imaging is also needed in certain circumstances.

Exercise testing uses the stimulus–response method of assessment. Accordingly, a standard exercise stimulus is applied to the testing subject via an ergometer, and the subject's physiological response is measured and later interpreted against recognized standards. The normative standard values are themselves compiled from typical responses to the exercise stress in a healthy matched population. Because the goal of exercise testing is to evaluate how organs and systems linking external (pulmonary) to internal (cellular) respiration perform under conditions of increased metabolic demand, the exercise stimulus is typically increased progressively and applied on large muscle groups, such as those used in running or riding a bicycle.

Treadmills and Cycle Ergometers

The motorized treadmill is the most commonly used apparatus for diagnostic purposes and for determination of functional capacity during exercise. The exercise stimulus is delivered by increasing the speed and/or grade (elevation) of the band on the treadmill. Maximal oxygen uptake is ≈10% higher on a treadmill than on a cycle ergometer.[13–16] An advantage of treadmill testing is that the majority of people are familiar with walking or running, including children as young as 3 years of age. However, even though almost any child older than 3 years can walk fast or run routinely, exercising on a treadmill is not a natural form of walking/running for anybody not familiar with exercising on a moving surface. Consequently, any patient who lacks experience walking on a treadmill should be tested only after having practiced and gained confidence in walking, running, and

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stepping on and off the treadmill. However, it is recommended to judge this on a case-by-case basis with consideration of the child's size, ability, and coordination.

A number of important practical disadvantages are associated with treadmill testing. It is inherently more dangerous than a cycle. It is also difficult to accurately quantify a subject's work rate during a treadmill test. The oxygen cost of running at a specific speed and grade is also hard to predict because it is affected by variables such as body size, weight, gait, and stride length. As a consequence, when a patient exercises on a treadmill, mechanical efficiency can only be estimated. Other disadvantages include high cost, large size, and noise. In addition, some measurements and specialized techniques, such as blood pressure and echocardiography, are difficult to obtain consistently on a treadmill because of noise or movement artifact.

Cycle ergometers typically are less expensive and less noisy and require less space than treadmills. Measurements of gas exchange and blood pressure, as well as ECG and echocardiography measurements, are easier to perform on subjects exercising on a cycle ergometer than on a treadmill. Thus, in most clinical circumstances, the cycle ergometer provides more reliable physiological measurements during exercise. However, some children, especially those 6 years and younger, may have difficulty keeping a steady cadence when pedaling, even when the cycle ergometer is adjusted to accommodate their size.

Two types of cycle ergometers exist, categorized by the manner in which the imposed work rate is controlled. Mechanically braked cycle ergometers control external work rate through frictional bands, whereas electronically braked ergometers increase resistance to pedaling electromagnetically. The main advantage of an electronically braked cycle ergometer over other ergometers is that it provides an accurate measurement of mechanical power output, thus permitting straightforward determination of work efficiency when accompanied by measurements of gas exchange. Electronically braked ergometers can deliver a "0" work rate for warm-up as well as a reliable constant work rate throughout a wide range of pedaling speeds (eg, 35 to 120 rpm) during exercise. Moreover, the oxygen cost of work is easily predictable on a cycle ergometer.[17]

Both modern electronically controlled treadmills and cycle ergometers permit the user to vary speed and grade or work rate rapidly and continuously either through panel settings or through preprogrammed exercise protocols. Consequently, the user can vary the set work rate in various fashions, such as step, square-wave, incremental, or ramp. Treadmills are easy to calibrate, whereas mechanically braked cycle ergometers require frequent calibration, and electronically braked cycle ergometers require specialized and expensive calibration equipment.[18–22]

Our recommendation is that exercise physiology laboratories that serve a pediatric population have available modern ergometers (treadmills and stationary bicycles) possessing features that facilitate the testing of children and the interpretation of their test results.

1. Electrophysiological Equipment

ECG recording is critical to stress testing for 3 purposes: (1) accurate assessment of heart rate to evaluate exercise effort and end point of the test; (2) diagnosis and evaluation of arrhythmia; and (3) assessment of conduction abnormalities and ST-segment and T-wave changes consistent with myocardial ischemia and QT interval. ECG recording leads should be placed after proper skin preparation to afford good-quality recording throughout the test. A 12-lead ECG should be recorded before the test. It is sometimes helpful to obtain these studies in supine and upright positions with and without hyperventilation to identify changes in T-wave morphology.

ECG recording equipment used for exercise testing should have a real-time display screen and a "writer" or printer to create copies of real-time or review ECGs. The display screen should be of adequate size so that it can be seen easily by the testing personnel during the study. It should display at least 3 leads of ECG in real time and ideally have a numeric display of instantaneous heart rate. Instantaneous "superimposition" scanning of median ECG complexes from selected leads can improve the sensitivity and rapidity of real-time detection of ST-segment changes during exercise. Analog ECG recording is acceptable, but digital acquisition has become more common to facilitate superimposition scanning and electronic storage. Digital recording should have a minimum sampling frequency of 1 mHz, but many systems improve the quality of recording with a frequency of 4 mHz. Configurable high- and low-pass filters, as well as a "line" or "notch" filter, can substantially improve the quality of ECG recording in a laboratory with numerous other electric devices. The writer should be capable of printing immediate copies of real-time ECG and continuous ECG rhythm strips. It is also convenient if it can print an ECG recorded previously during the study for review. Printing of median ECG complexes in the report at each stage can improve the efficiency of analysis by a subsequent interpreter. A computer-based recording system, in addition to facilitating report generation, can also provide "full-disclosure" review of ECG waveforms during a study. This allows review of arrhythmia or morphology changes that may have occurred when paper ECG recordings were not being created.

2. Blood Pressure Measurement

Blood pressure is an important variable to evaluate during exercise testing. In some cases, such as in evaluation of coarctation of the aorta or aortic stenosis, it may be one of the primary variables of interest. The circulatory changes that occur from a resting state to exercise are complex. Blood pressure is related to both cardiac output and peripheral vascular resistance. Both can change dramatically during exercise. The usual increase in cardiac output with exercise is thought to result in an increase in systolic blood pressure. Increasing exercise intensity results in increased cardiac output, and therefore systolic blood pressure should rise with each progressive stage of an exercise test. However, this response to exercise is variable, and healthy pediatric subjects may occasionally show only a modest increase in systolic pressure during exercise. The vasodilation seen with exercise

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generally causes the diastolic blood pressure to remain unchanged.[23]

A lack of appropriate increase in systolic blood pressure with exercise may indicate cardiac dysfunction. A fall in systolic blood pressure during exercise may be related to cardiac failure or to a left-sided obstructive lesion such as aortic stenosis.[24] It is important to remember that the sensitivity and specificity for a drop in systolic blood pressure with exertion for prediction of abnormal cardiac function are low. Such a drop can occur in individuals without severe cardiac abnormalities.[25]

It is generally recommended that blood pressure be measured (1) at rest before beginning the exercise test, (2) frequently during the exercise test to evaluate blood pressure elevation or to detect impending hypotension, and (3) during the recovery period to ensure that systolic blood pressure returns to near baseline values. In most tests, measurements every 3 minutes during exercise and recovery are adequate. However, more frequent measurements may be required if symptoms of hypotension are present.

To use blood pressure data with exercise testing, it is important to have accurate and reliable measurements. Extensive, useful information exists about the proper technique for measuring blood pressure at rest. Blood pressure determination during exercise is often more difficult, however, because of increased patient movement and ambient noise levels. These considerations underscore the need for rigorous attention to detail when blood pressure measurements are obtained during exercise.[26–28]

Most pediatric exercise laboratories use indirect measurement of blood pressure. Historically, auscultated blood pressure measurements were often obtained with the use of a mercury column for measurement. Recently, however, these devices have been phased out as hospitals have reduced their reliance on mercury-based technologies because of concerns about environmental toxicity.[29] An aneroid device is an acceptable alternative. However, these measurement devices require frequent calibration to ensure that they are comparable to a mercury column.[30–32] In recent years, automated devices have also become more prevalent. These devices usually employ oscillometric technology and are similar to the devices used for ambulatory blood pressure monitoring. These devices are also sensitive to movement and vibration. Consequently, they may not provide accurate measurements under some circumstances. These devices work by measuring the mean arterial pressure and calculating the systolic and diastolic blood pressure on the basis of oscillations detected in the blood pressure cuff through the use of proprietary algorithms. Using these devices may be particularly problematic in the evaluation of diastolic blood pressure.[33] It is important to evaluate the extent to which the device has been validated against measurements made by auscultation; some devices do not perform well when scrutinized in this manner.[33] There may even be variations among different models made by the same company. In addition, most testing of these devices is done under optimum resting conditions; their ability to perform adequately during exercise is often not known.

Whichever indirect method is chosen, the cuff size must be appropriate for the arm size of the patient. This means that pediatric exercise testing laboratories must have a variety of cuff sizes available. The cuff size selection should be based on the circumference of the arm. The cuff should completely encircle the arm. The width of the cuff bladder should be at least 40% of the arm circumference at the midpoint.[26] A blood pressure cuff that is too small will result in overestimation of the blood pressure and yield falsely high readings. Sphygmomanometers and cuffs should be cleaned and inspected on a regular basis. One hospital survey found that 21% of devices had technical problems that would limit accuracy[30]; another found >50% to have a defect.[34]

The person measuring blood pressure by auscultation is the most important factor in the acquisition of accurate and reliable blood pressure measurements. This individual must be properly trained in the methods of blood pressure determination and interpretation. The person must have good vision, hearing, and coordination between the eye, hand, and ear (for auscultatory measurements). Those who are measuring blood pressure should also undergo periodic retraining with evaluation of their technique.

Measurement of blood pressure is an important and often difficult component of the exercise test. Having the optimum equipment and well-trained observers is critical to success.

3. Pulse Oximetry

Oxyhemoglobin saturation is typically measured during exercise with a pulse oximeter. The 2 most commonly used types of oximeters measure the saturation at either the fingertip or ear lobe. Both types of probes are usually reliable if a good pulse is detected and the corresponding heart rate from the probe closely matches the heart rate obtained from the ECG equipment. In the absence of an adequate signal, the measurement is unreliable and will frequently underestimate the actual arterial oxygen saturation. Bright overhead lighting and darker skin pigmentation may also hinder detection of an adequate signal. In the presence of marked hypoxemia, pulse oximeters will also become unreliable and underestimate arterial saturation. Ensuring adequate surface contact and perfusion will improve the pulse oximeter reliability. If an ear probe is used, any ear jewelry that may interfere with the seating of the probe should be removed. Gently rubbing the lobe to improve local perfusion may also be helpful. When a finger probe is used, it is important to discourage the patient from tightly gripping the support bars or handlebars of the ergometer.

4. Metabolic Cart

In the past decade, commercially available metabolic carts have become standard equipment in most pediatric exercise laboratories. They are generally reliable, economical, and easy to maintain. Several of the more commonly used models interface with other equipment in the laboratory such as the ergometers, ECG recorders, and blood pressure measurement devices. Programs run by a standard personal computer usually control them. Data collected by the metabolic cart can be used by these programs to generate a complete summary report of the exercise testing. These programs can often interface with the hospital's database, allowing direct import-

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ing of exercise testing data into an individual patient's hospital record or database.

The determination of the ventilatory and pulmonary gas exchange responses to exercise requires measurement of either volume or airflow and the fractional concentrations of oxygen (F_{EO_2}) and carbon dioxide (F_{ECO_2}) in the expired air. From measurements of these 3 signals, valuable exercise variables and parameters can be determined and/or calculated. Among them are minute ventilation ($\dot{V}_E$), respiratory rate, and tidal volume (V_T), as well as oxygen uptake ($\dot{V}_{O_2}$) and carbon dioxide output ($\dot{V}_{CO_2}$). Other useful exercise variables that can be derived from these responses include ventilatory equivalent for oxygen ($\dot{V}_E/\dot{V}_{O_2}$) and carbon dioxide ($\dot{V}_E/\dot{V}_{CO_2}$), the end-tidal partial pressure of carbon dioxide (P_{ETCO_2}), and respiratory exchange ratio. Two parameters useful to evaluate functional capacity or endurance, namely, maximal oxygen uptake ($\dot{V}_{O_2}$max) and ventilatory anaerobic threshold (VAT), can be estimated from the time profile of the aforementioned variables.

Most exercise testing laboratories use automated medical gas analysis (MGA) systems or metabolic measurement carts (MMCs) for determining ventilatory and pulmonary gas exchange responses to exercise. These devices have become essential diagnostic tools, especially in patients with cardiac or pulmonary disorders. However, in laboratories with limited resources or in laboratories largely dedicated to conducting exercise research, it is not uncommon to find less complex automated systems that are tailored to the needs and the budget of the laboratory. The latter type of system has the advantage of providing greater control over the measurement process than MGA systems or MMCs.

There are more than a dozen manufacturers of MMCs. The most appropriate for the clinical setting are the laboratory-based and the semiportable systems. These systems provide high data density for ventilatory and gas exchange responses to diagnostic studies and research using a mixing chamber or a breath-by-breath mode. MMCs using the mixing chamber mode typically perform measurements of expired volume, F_{EO_2}, and F_{ECO_2} on a continuous basis averaging data every 15 to 20 seconds. Final reports are commonly data averages over 30 seconds. One of the disadvantages of using a mixing chamber to determine the exercise responses is the inability to determine simultaneously end-tidal variables such as end-tidal partial pressure of oxygen (P_{ETO_2}) and carbon dioxide (P_{ETCO_2}). In addition, gas exchange dynamics such as $\dot{V}_{O_2}$ kinetics and $\dot{V}_{CO_2}$ kinetics during constant–work-rate exercise are difficult to characterize with these systems. Nevertheless, for incremental exercise protocols such as those routinely used for clinical exercise testing, a well-designed mixing chamber–based automated system can provide accurate and precise information on pulmonary gas exchange that is comparable to that obtained from more sophisticated breath-by-breath systems.

Breath-by-breath systems are presently the most popular because of their ability to rapidly and flexibly process data and display information in various formats and at various time intervals and to provide abundant data even in patients with severe cardiopulmonary limitations capable of performing only brief exercise tests. Another major advantage of a breath-by-breath system is that it enables users to examine the transient gas exchange response in constant–work-rate protocols and at the termination of exercise.[35] These techniques provide sensitive tools for the evaluation of oxygen transport in both well-trained individuals and patients with cardiopulmonary disease. For a more detailed evaluation of automated metabolic gas analysis systems, refer to the report of Macfarlane.[36]

Regardless of whether a mixing chamber or a breath-by-breath system is used, care must be taken to ensure that the mouthpiece or mask used to collect expired air in children fits properly and that there are no air leaks. In smaller children and those patients with severe restrictive lung disease, care should be taken to ensure that the dead space of the system is not excessive. Closely fitting masks with a sealant gel may be more suitable for younger children who do not easily tolerate a mouthpiece and nose clip. When properly sealed and airtight, masks provide a more comfortable approach to collecting expired air in children and adolescents.

Using currently available MGA systems, many laboratories routinely measure $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ as well as their relationships to other parameters of exercise function. Oxygen uptake at maximal exercise ($\dot{V}_{O_2}$max) is the commonly used index of aerobic and cardiovascular fitness in both healthy and diseased pediatric populations. Common criteria to determine whether the child gave a maximal effort are as follows: (1) a respiratory exchange ratio ($\dot{V}_{CO_2}/\dot{V}_{O_2}$) >1.1; (2) a peak heart rate approaching 200 bpm (may not be attained in children with chronotropic or other limitations to exercise); and (3) subjective opinion of experienced testers. The adult criterion of $\dot{V}_{O_2}$ reaching a plateau with a further increase in work is often not observed in children. Reference values for healthy children and adolescents have been published for various ergometers, protocols, and populations.[1,37–40] Extensive data also exist on most of the more common types of congenital cardiac lesions.

The $\dot{V}_{O_2}$ at which the VAT occurs (often expressed as a percentage of predicted $\dot{V}_{O_2}$max) is also often used to reflect aerobic fitness. The VAT can be determined from plots of minute ventilation ($\dot{V}_E$) versus $\dot{V}_{O_2}$ or $\dot{V}_{CO_2}$ versus $\dot{V}_{O_2}$.[41] Most metabolic software will automatically compute the VAT, although sometimes it is not easily determined if the child has very limited exercise tolerance or if a nonramping protocol is used. Other measurements used to assess cardiopulmonary function evaluate $\dot{V}_{O_2}$ and $\dot{V}_{CO_2}$ responses relative to other measurements obtained during exercise. Some of the more commonly used measures include oxygen pulse, $\dot{V}_{O_2}$–work rate relationship, and the slope of the $\dot{V}_E$ versus $\dot{V}_{CO_2}$ relationship ($\dot{V}_E/\dot{V}_{CO_2}$ slope).

Oxygen pulse is the amount of oxygen consumed per heartbeat. It is calculated as O_2 Pulse$=\dot{V}_{O_2}$/HR, where HR is heart rate. On the basis of the Fick equation [$\dot{V}_{O_2}=$ HR$\times$SV$\times(a-v)O_2$], it is therefore the product of stroke volume (SV) and $(a-v)O_2$. The metabolic cart can be configured to plot oxygen pulse against exercise time or workload. Peak oxygen pulse is typically low in patients with a reduced rise in stroke volume during exercise, as the $(a-v)O_2$ difference at peak exercise approaches a maximum value that usually varies little in health and disease. If stroke

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volume fails to rise normally (or actually decreases) with increasing workload, a shallower than normal increase in oxygen pulse is noted. Normal values have been developed for both peak oxygen pulse and oxygen pulse slope.[39]

The $\dot{V}O_2$–work rate relationship is determined by the slope of the increase in $\dot{V}O_2$ for the increase in work rate and is a measure of the biochemical efficiency of exercise. Therefore, for exercise performed on a cycle ergometer, in which work can generally be quantified, $\dot{V}O_2$ normally increases at a rate of ≈8.5 to 11 mL/min per watt and is independent of sex, age, body weight, or height.[42] The metabolic cart can be configured to calculate the rate of rise in $\dot{V}O_2$ for a given work rate so that the aforementioned relationship may be examined. In children with reduced cardiac output, the rate of $\dot{V}O_2$ increase is not maintained as workload increases because there is a greater contribution of anaerobic work. This results in a less steep slope ($\Delta\dot{V}O_2/\Delta WR$), where WR is work rate.

The $\dot{V}E/\dot{V}CO_2$ slope is a measure of ventilatory efficiency that has been found to correlate with left ventricular ejection fraction in adults with congestive heart failure. Patients with impaired ventilatory efficiency have a greater ventilatory response for the same amount of expired CO_2. Within the pediatric population, this parameter has also proved to be a useful adjunctive measure in a variety of patients with congenital and acquired cardiovascular disease.

Noninvasive Measurement of Cardiac Output Using the Metabolic Cart

Various techniques have been used for noninvasive evaluation of cardiac output during exercise. Historically, the 3 most common techniques have included the CO_2 rebreathing method, acetylene rebreathing method, and use of continuous-wave Doppler echocardiography. All 3 techniques have their shortcomings and thus have largely been limited to use in the research setting. Recent software developments allow for a single-breath maneuver to be performed during exercise that may allow for assessment of cardiac output near peak exercise. The technique requires inhalation of an inert gas (acetylene) that is soluble in tissue and blood. The rate of alveolar absorption is proportional to the pulmonary capillary blood flow. The rate of absorption is determined by repeated measurements of the exhaled concentration of the gas obtained from a controlled single exhalation maneuver. The maneuvers required for both the single breath and rebreathing methods are often difficult for small children, especially at higher minute ventilation. This can often limit the usefulness of these techniques in the pediatric population.

5. Echocardiography Equipment

Accurate interpretation of wall motion abnormalities may be optimized by the use of a high-quality ultrasound system equipped with digital archiving and split- or quad-screen displays. This allows for a side-by-side comparison of resting and stress images. In pediatrics, systems with high frame rates, providing better temporal resolution, are optimal because the heart rate will be quite rapid during administration of stress. Additional equipment should include an ECG system equipped with a stress package enabling display and analysis of ST-segment trends, blood pressure monitor, and oximeter.[4] If a pharmacological agent is to be employed for stressing or if contrast agents will be administered, intravenous line equipment is necessary (see the protocol section).

6. Nuclear Myocardial Blood Flow Imaging

There is an increasing awareness of coronary perfusion abnormalities in children. These occur as a result of congenital coronary abnormalities and acquired coronary disease and as a consequence of corrective surgery for various congenital heart defects. The use of rest and stress nuclear myocardial blood flow imaging has increased significantly in the past decade.[5–9,43] Most maximal exercise protocols are acceptable for use with myocardial perfusion imaging (see section on exercise protocols). The only additional equipment requirement during an exercise test is the placement of a peripheral intravenous catheter in a nonexercising extremity. Nuclear myocardial blood flow imaging is frequently combined with pharmacological stress testing. This is especially true for younger patients or when imaging is combined with stress echocardiographic imaging. Specific additional equipment requirements for pharmacological stress testing will be discussed in the protocol section.

7. Spirometry Equipment

Spirometry is one of the more commonly performed pulmonary function tests. It provides a flow-volume loop and can assess the degree of airflow obstruction within the airways. Use of spirometry in conjunction with stress tests has become more common. This technique should be performed with the use of equipment and techniques that meet standards such as those developed by the American Thoracic Society.[44] Careful calibration, timing of the study, relationship of medication used at the time of the study, understanding of the correct spirometric technique, and maintaining the equipment are all essential components to achieve meaningful results. Although many of the commercially available spirometry systems provide computer algorithms for determining the acceptability of the patient's technique and interpretation of the study, the individual technician should have sufficient training in identifying the quality of the study and troubleshooting an individual test. Although training courses that are approved by the National Institute for Occupational Safety and Health exist, no approved courses exist for pediatric spirometry. Quality control via consultation with a trained pediatric pulmonary function technician or pediatric pulmonologist should help to optimize the use of spirometry.

8. Safety Equipment

In general, exercise testing is safe for children, even for children whose diagnoses place them in a high-risk group.[45] Nevertheless, it is essential that the exercise physiology laboratory be supplied with all the necessary equipment and drugs required to manage any emergency. A defibrillator must be present, tested periodically, and in working condition. Exercise testing personnel should be familiar with the circumstances that call for use of the defibrillator and the protocol to follow in case of an emergency. Oxygen should also be available in the exercise physiology laboratory, either in tanks or built in. In addition, a wall-mounted or portable suction system should be present. Emergency drugs should also be on hand and should be checked regularly to ensure that they are not outdated.

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TABLE 1. Common Reasons for Pediatric Stress Testing

1.	Evaluate specific signs or symptoms that are induced or aggravated by exercise
2.	Assess or identify abnormal responses to exercise in children with cardiac, pulmonary, or other organ disorders, including the presence of myocardial ischemia and arrhythmias
3.	Assess efficacy of specific medical or surgical treatments
4.	Assess functional capacity for recreational, athletic, and vocational activities
5.	Evaluate prognosis, including both baseline and serial testing measurements
6.	Establish baseline data for institution of cardiac, pulmonary, or musculoskeletal rehabilitation

IV. Indications and Contraindications for Stress Testing

The indications for stress testing in the pediatric age group are broad and have as a general goal the evaluation of exercise performance and the mechanisms that limit performance in the individual child or adolescent. In any individual test, the questions that need answers may vary on the basis of the child's clinical issues. Table 1 summarizes some of the more common indications for exercise testing in children. It is not inclusive, and others may occur for an individual patient.

Previous publications on cardiopulmonary exercise testing have included both absolute and relative contraindications that were extrapolated from standards and guidelines for adult exercise testing. Over the years, cardiopulmonary stress testing has become increasingly common in the pediatric population, including testing of patients previously considered to be at high risk. Patients with acute myocardial or pericardial inflammatory disease or patients with severe outflow obstruction in whom surgical intervention is clearly indicated should generally not be tested. As experience in the area of pediatric exercise testing has grown, the general safety of this procedure has been established, and there are now very few other absolute or relative contraindications to cardiopulmonary stress testing within the pediatric patient population.[1]

The benefit of testing in a controlled environment with medical supervision before allowing a child unrestricted activity is often thought to outweigh any procedure-related risks. Certain precautions, however, must be taken to ensure that the procedure is conducted in as safe an environment as possible and that all risks are minimized.[1] It is useful to distinguish between patients at low risk for adverse events and patients at higher risk for adverse events. A physician should be on standby in case of unforeseen complications arising during a low-risk test, and a physician should be present during testing when the test is considered higher risk. Data on current practice for testing of lower- and higher-risk patients are provided in Table 2 and are discussed later in this statement.

TABLE 2. Relative Risks for Stress Testing

Lower Risk	Higher Risk
Symptoms during exercise in an otherwise healthy child who has a normal CVS exam and ECG	Patients with pulmonary hypertension
Exercise-induced bronchospasm studies in the absence of severe resting airways obstruction	Patients with documented long-QTc syndrome
Asymptomatic patients undergoing evaluation for possible long-QTc syndrome	Patients with dilated/restrictive cardiomyopathy with CHF or arrhythmia
Asymptomatic ventricular ectopy in patients with structurally normal hearts	Patients with a history of a hemodynamically unstable arrhythmia
Patients with unrepaired or residual congenital cardiac lesions who are asymptomatic at rest, including 1. Left to right shunts (ASD, VSD, PDA, PAPVR) 2. Obstructive right heart lesions without severe resting obstruction (TS, PS, ToF) 3. Obstructive left heart lesions without severe resting obstruction (cor triatriatum, MS, AS, CoA) 4. Regurgitant lesions regardless of severity	Patients with hypertrophic cardiomyopathy who have 1. Symptoms 2. Greater than mild LVOTO 3. Documented arrhythmia
Routine follow-up of asymptomatic patients at risk for myocardial ischemia, including 1. Kawasaki disease without giant aneurysms or known coronary stenosis 2. After repair of anomalous LCA 3. After arterial switch procedure	Patients with greater than moderate airways obstruction on baseline pulmonary function tests
Routine monitoring in cardiac transplant patients not currently experiencing rejection	Patients with Marfan syndrome and activity-related chest pain in whom a noncardiac cause of chest pain is suspected
Patients with palliated cardiac lesions without uncompensated CHF, arrhythmia, or extreme cyanosis	Patients suspected to have myocardial ischemia with exertion Routine testing of patients with Marfan syndrome
Patients with a history of hemodynamically stable SVT	Unexplained syncope with exercise
Patients with stable dilated cardiomyopathy without uncompensated CHF or documented arrhythmia	

CVS indicates cardiovascular system; ASD, atrial septal defect; VSD, ventricular septal defect; PDA, patent ductus arteriosus; PAPVR, partial anomalous pulmonary venous return; TS, tricuspid stenosis; PS, pulmonary stenosis; ToF, tetralogy of Fallot; MS, mitral stenosis; AS, aortic stenosis; CoA, coarctation of aorta; LCA, left coronary artery; SVT, supraventricular tachycardia; CHF, congestive heart failure; and LVOTO, left ventricular outflow tract obstruction.

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TABLE 3. Stress Protocols

Protocols	Uses
1. Multistage incremental Treadmill Bruce Balke Cycle James McMaster Strong	Measurement of maximal oxygen consumption, anaerobic threshold, measurement or estimation of maximal power output, assessment of causes of exercise limitation, assessment of myocardial ischemia or arrhythmias
2. Progressive incremental cycle ergometer protocols: 1-minute, incremental ramp	Same as multistage incremental, measurements of work and ventilatory efficiency
3. Constant work rate protocols	Measurement of kinetic responses of oxygen consumption or heart rate to brief episodes of exercise
4. Sprint protocols	Exercise-induced bronchospasm
5. Six-minute walk	Assessment of exercise tolerance in moderately to severely limited children

Indications for Exercise Testing Termination

Cardiopulmonary stress testing is often performed to elicit symptoms and to assess cardiac and pulmonary reserves. It is thus desirable to achieve a maximal study in most instances, and care must be taken not to terminate a test too quickly. Three general indications to terminate an exercise test exist: (1) when diagnostic findings have been established and further testing would not yield any additional information; (2) when monitoring equipment fails; and (3) when signs or symptoms indicate that further testing may compromise the patient's well-being. An attempt should be made to identify quickly the source of the patient's symptoms before termination of the test so that a test is not terminated prematurely. For example, dizziness during exercise may indicate reduced cardiac output, but if a patient's blood pressure is rising appropriately, and there is a normal heart rhythm with a normal rise in heart rate and oxygen pulse, the dizziness is not likely due to inappropriately low cardiac output but rather another cause. Provided that the dizziness is not severe, ongoing exercise may help to clarify the origin. Cardiac and pulmonary parameters should be monitored closely. Clinical judgment should always be used, and test termination is usually indicated if the following occur:

1. Decrease in ventricular rate with increasing workload associated with extreme fatigue, dizziness, or other symptoms suggestive of insufficient cardiac output;
2. Failure of heart rate to increase with exercise, and extreme fatigue, dizziness, or other symptoms suggestive of insufficient cardiac output;
3. Progressive fall in systolic blood pressure with increasing workload;
4. Severe hypertension, >250 mm Hg systolic or 125 mm Hg diastolic, or blood pressures higher than can be measured by the laboratory equipment;
5. Dyspnea that the patient finds intolerable;
6. Symptomatic tachycardia that the patient finds intolerable;
7. Progressive fall in oxygen saturation to <90% or a 10-point drop from resting saturation in a patient who is symptomatic;
8. Presence of ≥3 mm flat or downward sloping ST-segment depression;
9. Increasing ventricular ectopy with increasing workload, including a >3-beat run;
10. Patient requests termination of the study.

In all cases, a decision to terminate a stress test should be based on the totality of the available data rather than rigid guidelines.

V. Protocols

Many protocols have been used in the past to evaluate exercise performance or functional capacity in children. Ultimately, the protocol selected for exercise testing will depend on the purpose of the test and the characteristics of the patient. Nevertheless, the main criterion to guarantee obtaining a maximum oxygen uptake and good reproducibility of exercise parameters (eg, ventilatory anaerobic threshold) with a particular exercise protocol on a particular individual is that the exercise protocol should be designed to have the subject reach his or her limit of tolerance in 10±2 minutes.

In principle, many distinct protocols can be implemented and used on either a treadmill or a cycle ergometer. However, to facilitate comparisons with established normative values, standard exercise protocols have been developed that are suitable for most clinical and research applications. The most commonly used protocols fall into one of the following 3 categories: (1) multistage incremental (every 2 or 3 minutes, with a "pseudo" steady state at each stage); (2) progressive incremental (every minute) or continuously increasing (ramp); (3) constant work rate (5 to 10 minutes). In all cases, the exercise protocol is typically preceded by baseline (3 minutes) and warm-up (3 minutes) measurements as well as followed by recovery measurements (5 to 10 minutes). Protocol types and their usages are summarized in Table 3.

Multistage Incremental Protocols

Multistage incremental protocols are the most commonly used protocols clinically, mainly because estimation or measurement of $\dot{V}O_2$max can be obtained relatively easily with simple modern equipment. Most protocols that fall

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into this category permit determination of $\dot{V}O_2$max; however, the Bruce[46–48] and the Balke[49] treadmill protocols and the James[50] and the McMaster cycle ergometer protocols are the most commonly used.[51]

Treadmill Protocols

Bruce Protocol

The Bruce protocol was designed originally for diagnosing coronary artery disease in adults, but it has great popularity among pediatric cardiologists. Cumming et al[48] provided normative data on the exercise responses and endurance times using the Bruce protocol in 327 children aged 4 to 14 years. One of the major advantages of using this protocol is that it can be used on subjects of all ages, and thus it can provide comparative exercise data using the same protocol as a child grows. Other advantages are that exercise responses to submaximal work rates can be measured (eg, $\dot{V}O_2$ and cardiac output) and that $\dot{V}O_2$max can be estimated from determination of endurance time (r=0.88). However, the Bruce protocol has some practical disadvantages. For younger or more limited children, the work increments between successive stages may be too great, resulting in the tendency for subjects to quit during the first minute of a new 3-minute stage. For subjects who are well trained, the first 4 stages of the Bruce protocol are too slow, leading to boredom. In addition, the most appropriate running speeds for these young athletes occur at very high elevations (>18%). The 3-minute stages are too long and thus boring for young subjects. In general, regardless of degree of fitness of the individual, most exercise is performed at relatively steep grades when the Bruce protocol is used, which encourages subjects to hold onto the handrails, thereby affecting the oxygen cost of exercise significantly.[20] In addition, the large increases in speed and grade may limit the ability to accurately measure submaximal metabolic data such as the anaerobic threshold.

Balke Protocol

The Balke protocol involves increases in slope while the treadmill speed is kept constant (3.5 mph). As in the case of the Bruce protocol, the Balke protocol is rather limited when one attempts to obtain appropriate exercise responses in a reasonable amount of time (8 to 10 minutes) in populations of children ranging from very unfit to highly fit, from 6 to 18 years of age, or from normal healthy to chronically ill children. The use of the same treadmill protocol for highly diverse and heterogeneous populations is impractical and has led to variations of the original protocol. A modified version of the Balke protocol ("modified Balke") has been used to test chronically ill children as well as healthy children with varying fitness levels. Modified versions of the Balke protocol using faster constant speeds ("running Balke") have also been implemented and tested in fit individuals and active children. The modified Balke seems to be well suited to test unfit, obese, chronically ill, and very young children.[52] The running Balke is more suitable for active and fit young subjects.[53] In general, the Balke protocol may be modified to tailor it to the subject's age and fitness level by adjusting the constant treadmill speed and by starting at a higher grade.[54] The goal is to keep the exercise time between 8 and 10 minutes.

Cycle Protocols

James Protocol

The James protocol separates subjects into 3 specific exercise protocols consisting of 3 progressive 3-minute stages at predetermined work rates based on gender and body surface area. After completion of these 3 stages, work rate is increased by ≈100 or 200 kpm/min (18 or 36 W/min) until a maximal voluntary effort is reached. Normative data in children have been provided by James et al[50] and Washington et al.[55] This protocol has some limitations when applied to small children or children with moderate to severe exercise intolerance in whom test duration may range between 4.5 and 7 minutes, thus providing limited data for analysis.

McMaster Protocol

The McMaster protocol separates subjects into 3 specific exercise protocols of 2-minute stages at predetermined work rates based on gender and height. The work rate increments in this protocol are linear, and the 2-minute duration of each stage seems to be long enough to achieve a pseudo-steady state for most physiological variables.[56]

Strong Protocol

The Strong protocol separates subjects into 4 specific exercise protocols of 3-minute stages at work rates based on the subject's weight. The goal of the protocol is to determine physical working capacity at a heart rate of 170 bpm. Normative data have been provided by Alpert et al.[57]

Progressive Incremental Cycle Ergometer Protocols

In this category, we include continuously incremental (ramp) protocols and protocols in which each stage lasts 1 minute. This kind of protocol is very efficient in providing exercise responses in a short amount of time, thus enabling acquisition of diagnostic data within 10 to 12 minutes.[38,58] The first 1-minute incremental protocol that was systematically used in pediatric patients was the Godfrey test. This protocol separates subjects into 3 groups identified by height, and the work rate increment was chosen to be 10 or 20 W. Normative data for children using this protocol have been published.[59] The first study systematically using a ramp protocol in children was conducted by Cooper et al.[38] Normative data on 109 children were reported in this study. In general, ramp and 1-minute incremental protocols have been reported to induce similar exercise responses.[60–62] Ideally, the slope of the ramp should be tailored to have subjects terminate the test within 10 minutes and is based on the child's body size and physical condition. A good estimate of this slope is S (W/min)= (predicted $\dot{V}O_2$max$-\dot{V}O_2$ unloaded)/92.5.[63] However, in most cases a slope (ie, work rate increment per minute) is selected on a case-by-case basis. An appropriate work rate increment for fit adolescents may be 20 to 25 W/min, whereas for unfit patients and young children it may be 10 W/min. For normal children, a work rate increment relative to body weight (3.5 $W \cdot min^{-1} \cdot kg^{-1}$) has been suggested by Tanner el al.[62]

Even though ramp protocols do not permit a steady state, the ramplike change in work rate elicits submaximal responses that are equivalent to those derived from incremental protocols with stages lasting 2 to 3 minutes. However, to

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establish this correspondence and to interpret properly submaximal ramp responses, appropriate analysis is required.[64–66] Consequently, because (1) most important exercise responses (eg, cardiac output, oxygen uptake, minute ventilation, heart rate) during exercise in children have response times <1 minute; (2) work rate increment is typically <30 W/min in pediatric subjects; and (3) desired submaximal measurements (eg, cardiac output) take <15 seconds to be completed, valid submaximal physiological responses to ramp changes in work rate can be obtained if appropriate and careful data analysis is performed.[67–70]

Constant–Work-Rate Protocols

Submaximal constant–work-rate exercise tests of 5 to 10 minutes' duration are becoming more common in clinical exercise laboratories as an alternative protocol to maximal exercise tests. This is partly because submaximal exercise tests overcome some of the limitations of maximal exercise testing, which include (1) dependence on the patient's effort; (2) low sensitivity for measuring changes induced by therapeutic interventions; and (3) poor correlation with energy expenditure during activities of daily living, patient symptoms, and quality of life. The kinetic responses of oxygen uptake and/or heart rate at the onset of a brief bout of constant–work-rate exercise or during the recovery from the exercise bout can provide valuable information about the patient's ability to cope with the numerous changes in energy demand encountered in everyday life. A simple measurement, such as heart rate taken after a constant–work-rate exercise bout at an intensity that elicits a heart rate that corresponds to 70% to 85% of predicted maximum heart rate for the person's age, can have great predictive value. Indeed, a study conducted in a large adult population strongly suggests that the rate of heart rate recovery after submaximal exercise is associated with the person's risk of death. The longer it takes the heart rate to return to normal values, the greater the risk for death. When the observed patterns of physical activity in children are considered, submaximal exercise bouts of 1-minute duration at a work rate corresponding to ≈90% of predicted maximum heart rate are more appropriate in a pediatric population. However, to date, reference values for healthy children and adolescents are not readily available for comparison.

Alternative Protocols

Six-Minute Walk Test

A 6-minute walk test may be more appropriate for assessing exercise tolerance in children with moderate to severe exercise limitation for whom traditional exercise testing may be too stressful. Guidelines established by the American Thoracic Society[71] should be followed. Basically, the patient is encouraged to try to cover as much distance or as many laps on a measured course (often 30 m) as possible in 6 minutes. Patients using supplemental oxygen should perform the test with oxygen. Although many walk tests are done without monitoring, portable oximeters are available that enable continuous monitoring of both oxyhemoglobin saturation and heart rate without negligible additional weight. In the absence of portable equipment, it may be useful to monitor oxyhemoglobin saturation and heart rate before, during, and after the test. The patient is permitted to stop and rest but should resume walking if possible during the 6-minute period. Standard encouragement as outlined by the American Thoracic Society guidelines should be given. The total distance walked is the primary outcome. It has been suggested that distance walked should be multiplied by the patient's weight to reflect the work of walking.[72] At least 2 practice tests performed on a separate day are advisable to minimize a learning effect and avoid fatigue. Because of the self-paced, submaximal nature of this test, the results may be more applicable than maximal exercise testing to everyday activities that the child may encounter. At this time, reference values for healthy children and adolescents are not readily available for comparison. However, the test is useful for following disease progression or measuring the response to medical interventions. The test is not as useful for healthier patients whose distance walked may be limited by leg length or height more than disease.[71,72]

Exercise-Induced Bronchospasm Provocation

The exercise-induced bronchospasm (EIB) provocation allows for quantification of bronchial reactivity as measured by spirometry that is induced while a subject exercises for 5 to 8 minutes on a treadmill at an intensity of 80% of maximum capacity. The treadmill is preferable to cycle testing because it is more prone to induce bronchospasm. Additionally, the exercise room should be as cool (temperature 20°C to 25°C) and as dry as possible (relative humidity <50%) to elicit the best response.[73] Both of these parameters should be recorded for each test. If feasible, some evidence indicates that having the child breathe very cold air (−20°C) can increase the sensitivity of the exercise challenge.[74] The exercise protocol should quickly increase the intensity to 80% of maximal capacity (using predicted heart rate maximum as a surrogate) within 2 minutes. If the intensity is not reached quickly, the likelihood of refractoriness to the development of bronchospasm will greatly increase. An incremental work rate used in many cardiopulmonary exercise tests (ie, Bruce treadmill or Godfrey cycle protocols) is less likely to be effective in evaluating EIB because of its short duration of high ventilation and thus should be avoided in the evaluation of EIB. Additionally, use of prolonged warm-up periods may also induce refractoriness to EIB.

Exercise is preceded by baseline spirometry. Spirometry is repeated immediately after exercise and again at minutes 5, 10, and 15 of recovery. Most pulmonary function test nadirs occur within 5 to 10 minutes after exercise. If the child becomes symptomatic during or after testing even in the absence of a significant forced expiratory volume in 1 second (FEV_1) decline, a bronchodilator may need to be administered. Trained respiratory personnel should be available during and after exercise. Accepted criteria for a significant decline in FEV_1 after exercise are variable. Declines of 12% to 15% in FEV_1 are typically diagnostic.

Use of medications before testing should be considered in part on the basis of the clinical question being asked. Consultation with the child's primary care physician or asthma specialist will help to optimize the testing procedure.[73]

Pharmacological Stress Protocols

Pharmacological stress testing is generally used when conventional exercise testing is unsuitable or impractical. These circumstances may include patients who are too young or are

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TABLE 4. Institutions Performing Specialized Testing

Type of Study	No. of Institutions	Percentage
Exercise-induced asthma/pulmonary testing	19	83
Pharmacological stress testing	11	48
Stress echocardiography	13	57
Nuclear myocardial blood flow imaging	7	30
Cold-air challenge	2	9

unable to perform exercise testing or in cases in which the motion of exercise may interfere with data collection. Such cases may include certain types of echocardiographic studies (see echocardiography protocols below).

Pharmacological stress testing is usually performed at the site where additional studies will occur, such as the echocardiography laboratory or the nuclear imaging suite. The patients require a peripheral intravenous line for the infusion of the pharmacological stress agent. Additional equipment will include appropriate infusion pumps, 12-lead ECG monitoring system, and blood pressure–monitoring equipment. Sedation is rarely needed but may be required for young patients or those patients with limited ability to cooperate with the testing protocol.

Two basic types of pharmacological agents exist: those that increase myocardial oxygen consumption and those that cause coronary vasodilatation. Dobutamine and isoproterenol are examples of the former and, to an extent, simulate the effects of exercise. Adenosine causes dilation of normal coronary artery segments, resulting in a shunting of myocardial blood flow away from diseased segments. Dipyridamole inhibits adenosine reuptake, resulting in the same physiology.

Dobutamine is administered in gradually increasing doses from a starting dose of 10 to a maximal dose of 50 μg/kg per minute in 3- to 5-minute stages. Atropine (0.01 mg/kg up to 0.25-mg aliquots given every 1 to 2 minutes up to a maximum dose of 1 mg) can be administered to augment heart rate as needed. In children, a dobutamine dose of 50 μg/kg per minute is usually required to achieve the target heart rate. Atropine is needed in approximately two thirds of patients and is usually administered at 40 or 50 μg/kg per minute of dobutamine. Esmolol (10-mg/mL dilution, not the 250-mg/mL dilution used for continuous intravenous infusion) at a dose of 0.5 mg/kg should be available to rapidly reverse the effects of dobutamine in the event of adverse reactions or development of ischemia.[4,75]

If echocardiographic imaging is performed, the imaging should be obtained at rest and at each dosing stage. Radioisotopes for nuclear myocardial blood flow imaging should be injected 1 minute before the infusion of dobutamine at maximal dosage is stopped.

Adenosine is infused at 140 μg/kg per minute for 6 minutes. If performed, echocardiographic imaging should be continuous

TABLE 5. Current Test Practices of Responding Laboratories

	No. of Institutions (%)		
Diagnostic Category	Physician Present	Physician Immediately Available	Would Not Test
Normal exam and ECG with exercise symptoms	15 (65)	8 (35)	...
EIB without severely abnormal resting spirometry	13 (56)	9 (39)	1 (4)
Asymptomatic patient to evaluate long QTc	19 (84)	4 (16)	...
Asymptomatic ventricular ectopy with structurally normal heart	15 (65)	6 (24)	1 (4)
Asymptomatic left-to-right shunt lesions	15 (65)	6 (24)	1 (4)
Mild to moderate right heart obstructive lesions	19 (83)	3 (13)	1 (4)
Mild to moderate regurgitant lesions	...	...	...
Routine testing of asymptomatic patients at risk for myocardial ischemia	17 (74)	5 (22)	1 (4)
Routine testing after heart transplantation	13 (56)	5 (22)	5 (22)
Hemodynamically stable supraventricular tachycardia	13 (56)	5 (22)	5 (22)
Palliated single ventricles	17 (74)	4 (16)	2 (9)
Cardiomyopathy without failure	17 (74)	5 (22)	1 (4)
Moderate left or right ventricular outflow obstruction	18 (78)	...	5 (22)
Pulmonary hypertension	15 (65)	...	8 (35)
Documented long QTc	20 (87)	...	2 (9)
Cardiomyopathy with evidence of failure	18 (78)	...	2 (9)
Severe baseline airway obstruction	8 (35)	2 (9)	3 (13)
Suspected exertional myocardial ischemia	20 (87)	...	3 (13)
Acute myocarditis/pericarditis	5 (22)	...	18 (78)
Severe aortic or pulmonary stenosis	5 (22)	...	18 (78)
Uncontrolled resting hypertension	7 (30)	...	16 (70)
Routine testing on Marfan patients	11 (48)	3 (13)	9 (39)
Unstable arrhythmia	10 (43)	...	13 (56)

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throughout the infusion. Nuclear isotope injection is performed at 3 minutes into the infusion. Dipyridamole is infused over the same time period at a dose of 0.6 mg/kg per minute. Radioisotope delivery and echocardiographic imaging should be performed at the peak physiological effect of the dipyridamole, usually 3 to 4 minutes after completion of the infusion. Administration of aminophylline is routinely used in many centers after termination of the dipyridamole infusion.[4,7,43]

The occurrence rate of significant adverse reactions to pharmacological stress in the pediatric population is unknown. However, reports in recent literature suggest that the rate is quite low. Nevertheless, care must be taken to ensure patient safety. Heart rate, rhythm, and ST-segment changes should be closely monitored throughout the study and in the immediate poststudy period. Patients should be observed for any complaints or signs of chest pain, hypotension, or bronchospasm. Prompt termination of the infusion and reversal of the stress agent should be undertaken in any of these circumstances.

Echocardiography

Two basic types of exercise are used with echocardiography: treadmill and cycle ergometry (upright or supine). With treadmill and upright cycle testing, echocardiography is usually performed before exercise and immediately after exercise termination (within 60 to 90 seconds). In the case of supine cycle ergometry, echocardiography is performed before and during all stages of exercise (including peak). Oxygen consumption and cardiac output determinations can also be obtained. When pharmacological stress agents are used, imaging is performed as outlined in the section on pharmacological stress protocols.[4]

VI. Current Practice

In an attempt to determine the current practices in pediatric cardiovascular exercise laboratories, a survey was sent to all institutions listed by the AHA as having a pediatric cardiology training program. Forty-eight institutions were contacted, with 23 institutions (48%) submitting an answered questionnaire. Because of the anonymous nature of this survey, no data are available on the size or geographic location of the responding centers versus the entire contacted group.

Figure 2 shows the distribution of the number of studies performed by the responding institutions. Sixty-one percent performed >200 studies a year, but almost 35% performed ≤150. The laboratories had a range of 0 to 3 technicians dedicated to performing these studies. Most institutions (n=15) had either 1 or 2 technicians dedicated to the exercise laboratory. Seventeen of the 23 institutions had at least 1 technician who was trained in exercise physiology at either a bachelor's or master's degree level.

In the 3 years preceding the survey, each institution was asked to list the number of complications occurring in their laboratory that required medical intervention. They were specifically asked to exclude events that the testing was meant to provoke (eg, the occurrence of supraventricular tachycardia in a patient suspected to have exercise-induced supraventricular tachycardia). A total of 4 events occurred in

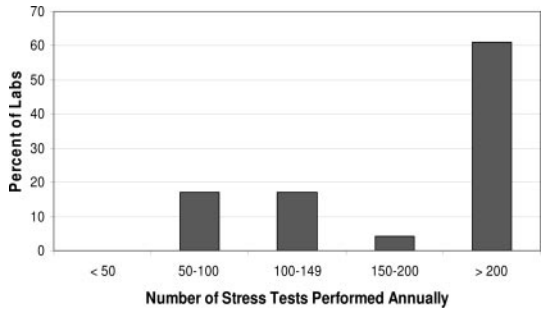

Figure 2. Percentage of the responding centers performing various annual ranges of stress tests.

all 23 institutions over the 3-year period. If it is assumed that each institution performed only the minimum number of tests in its reported range (Figure 2), this would yield a complication rate of 0.035%. Obviously, because many institutions performed >200 studies per year, the actual complication rate is most likely significantly lower. Nonetheless, even from this very conservative estimate, the risk involved in pediatric stress testing appears to be extremely low.

All but 3 institutions required at least 2 people to be present to supervise all testing. Physicians were present in the laboratory for all testing in 70% of the institutions. They were immediately available but not necessarily in the laboratory for the additional 30% of the institutions. Informed consent was obtained in 48% of the laboratories.

Standard cardiovascular exercise testing was performed principally with the use of a treadmill ergometer. A median of 70% (range, 0% to 100%) of the studies were performed on a treadmill, with 30% (range, 0% to 100%) performed on a stationary cycle ergometer. Table 4 shows the percentage of institutions performing various specialized testing procedures.

Table 5 shows the current practice of the responding institutions for performance of stress testing on various diagnostic groups. These correspond to the groups listed as lower or higher risks in Table 2. These results indicate that all responding centers require at least the immediate availability of a physician during testing regardless of the severity of the patient's diagnosis or symptoms. In all categories a majority of the laboratories performing testing required a physician to be physically present for the procedure, although the extremely low complication rate brings this practice into question.

The majority of the laboratories would not test 6 diagnostic categories (Table 5). All 6 are listed under "higher risk" or "testing would not be advised" in this statement. In all diagnostic groups listed as higher risk, the vast majority of institutions required a physician to be immediately present or they would not test the patient (Table 5).

The results of this survey suggest a broad range of practice in the pediatric exercise physiology laboratories with regard to the number of tests performed, number of personnel, and formal training of personnel. On the other hand, there appears to be a fairly uniform approach to physician presence during testing and the approach to testing patients in high-risk diagnostic categories. However, this survey included only centers with fellowship programs, and practices in other types of programs may vary from these findings. Most importantly,

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it is clear that stress testing as currently performed in the pediatric population is very safe and carries an extremely low risk of medical complications.

VII. Summary

The role of stress testing in the management of children and adolescents with both cardiovascular and noncardiovascular diagnoses and symptoms continues to increase. To perform these procedures properly, a complete understanding of exercise physiology in children is essential. Proper training of personnel and proper staffing of the pediatric exercise physiology laboratories are required to ensure the safety of patients and ensure that the desired testing information is accurately obtained. For these reasons, pediatric testing should remain an integral part of pediatric cardiology training.

Authors' Disclosures

Writing Group Member	Employment	Research Grant	Other Research Support	Speakers Bureau/ Honoraria	Ownership Interest	Consultant/ Advisory Board	Other
Stephen Paridon	Children's Hospital of Philadelphia	None	None	None	None	Bristol-Myers Squibb*	None
Steve Boas	Children's Asthma Respiratory & Exercise Specialists, Glenview, Ill	None	None	None	None	None	None
Marco Cabrera	Case Western Reserve University, Cleveland, Ohio	None	None	None	None	None	None
Stephen R. Daniels	University of Cincinnati–Children's Hospital Medical Center	None	None	None	None	None	None
Thomas Kimball	University of Cincinnati–Children's Hospital Medical Center	None	None	None	None	None	None
Timothy Knilans	University of Cincinnati–Children's Hospital Medical Center	None	None	None	None	None	None
Laura Kraft Caldarera	Child Cardiology Associates, Rockville, Md	None	None	None	None	None	None
Patricia A. Nixon	Wake Forest University, Winston-Salem, NC	None	None	None	None	None	None
Angela Yetman	The Children's Hospital, Denver, Colo	None	None	None	None	None	None
Jonathan Rhodes	Children's Hospital Boston	None	None	None	None	None	None
Bruce Alpert	University of Tennessee, Memphis	None	None	None	None	None	None

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*Modest.

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David J. Driscoll	Mayo Clinic	None	None	None	None	None	None
Robert P. Garofano	New York Presbyterian Hospital, Columbia Presbyterian Campus	None	None	None	None	None	None
Michael G. McBride	Children's Hospital of Philadelphia	None	None	None	None	None	None
Thomas W. Rowland	Baystate Medical Center, Children's Hospital	None	None	None	None	None	None

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