Exercise testing in pediatrics

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The importance of regular exercise cannot be overemphasized. Physical activity in American children has diminished for a variety of reasons as society has trended away from outdoor activities toward sedentary entertainment, including television, video games, and computers. Healthy levels of physical fitness require regular participation (four to five times per week) in activities that generate energy expenditures significantly above the resting level and ideally greater than 50% to 60% of maximal exertion [1].

No discussion of exercise testing can be effectively understood without first reviewing the physiologic responses to exercise. Optimal exercise performance requires a continuous meshing of multiple organ systems [2]. Any malfunctioning of the muscles, bones, or nervous system will impair exercise performance. Exercise testing provides a unique insight by uncovering deficiencies or abnormalities not detectable in the resting state [3]. Inadequate conditioning of the musculoskeletal system either from chronic illness or sedentary living also potentially impairs performance [4]. Equally important to exercise performance is the function of the support organs (ie, the cardiovascular and pulmonary systems) during exercise (Fig. 1). The roles of the heart and lungs are to provide adequate energy substrates to working muscle and to remove the end products of aerobic and anaerobic metabolism during exercise. The authors briefly review the normal physiologic response to exercise. They then discuss populations in which exercise testing is most useful, the indications and contraindications for graded exercise, and the usual parameters that are measured during testing. Finally, the
authors review some of the recent data on exercise performance in specific pediatric populations.

Changes in the cardiovascular and pulmonary systems in the normal patient during dynamic exercise

In the healthy individual, cardiac output may increase fivefold during exercise as a result of an increase in stroke volume and heart rate. This increased output is not evenly distributed. The muscles, heart, and skin (to effectuate proper cooling) are the primary recipients of this increased blood flow. Other vital organs such as the gut, kidneys, and central nervous system see no significant changes in blood flow during exercise. Therefore, exercise can be thought of as the state of increased sympathetic tone overridden by local metabolic vasoregulation.

Local metabolic vasoregulation results in a regional vasodilatation in muscle, skin, and heart. Local production of potassium, hydrogen, lactate, carbon dioxide, and adenosine nucleotides contributes to maintaining local vasodilatation of blood vessels serving the exercising muscles. These metabolites, along with the increased heat production of working muscle, contribute to the rightward shift of the oxyhemoglobin dissociation curve, thereby favoring more unloading of oxygen to working muscle. The net effect of local vasodilatation is a significant drop in systemic vascular resistance during exercise when large muscle groups are constantly in motion (so-called “dynamic exercise”). This drop in vascular
resistance occurs despite an increase in sympathetic tone. Pulmonary vascular resistance also falls significantly during exercise as a result of dilation of the pulmonary vascular bed. The overall result is a fall of resistances against which both the left and right ventricles pump.

During early exercise, the increase in cardiac output is caused by an increase in both stroke volume and heart rate. Stroke volume may increase 40% to 60% above resting levels. As exercise intensifies, however, additional increases in cardiac output are caused almost exclusively by an increasing heart rate. Therefore, oxygen consumption by working muscles is tightly linked to heart rate, and these variables have an almost linear relationship during exercise. (This relationship is discussed further when the authors discuss limitations of exercise in patients with chronotropic impairment.) To some degree, the exercising individual may be able to compensate for an impairment of either stroke volume or heart rate by increasing oxygen extraction by working muscle (arterio-venous oxygen difference) or by an increase in anaerobic metabolism. Both of these mechanisms are limited and cannot compensate for significant impairment of cardiac output.

**Indications for exercise stress testing**

Most pediatric patients undergo exercise testing for evaluation of nonischemic heart disease. The most common reason is the evaluation of exercise performance in preoperative or postoperative congenital heart defects. Other common indications include cardiomyopathies, exercise-induced symptoms including palpitations or syncope, possible arrhythmias during exercise, or syncope, possible arrhythmias during exercise.

**Box 1. Indications for performing an exercise test**

- To evaluate specific symptoms or signs induced by exercise
- To identify abnormal adaptive responses to exercise in cardiac or noncardiac disorders
- To assess the effectiveness of medical or surgical interventions
- To assess functional capacity for vocational, recreational, and athletic recommendations
- To discover the prognosis for a specific disorder
- To evaluate overall fitness levels
- To establish baseline data for follow-up of rehabilitation programs

and suspected pulmonary disorders such as exercise-induced bronchospasm (Box 1) [3].

**Risk to the patient and contraindications to exercise testing**

The actual risk of exercise testing in the pediatric population is believed to be quite low. Indeed, in adults, exercise entails a small risk: data confirm up to 1 myocardial infarction or death per 2500 tests [5]. Given that ischemic heart disease is rare in the pediatric population, the authors estimate the risk is far less than in adults.

Exercise physiologists generally agree that there are absolute and relative contraindications to graded exercise testing (Box 2). Before the test, all patients must have a complete medical evaluation by a physician. In some cases, additional studies are also warranted, such as a baseline ECG, echocardiogram, 24-hour Holter monitoring, or pulmonary function testing. Rowland [3] lists conditions that warrant special considerations, including severe aortic stenosis, severe pulmonary stenosis, un repaired coronary arterial abnormalities, bleeding

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**Box 2. Contraindications to exercise testing**

**Absolute contraindications**

- Active inflammatory heart disease
- Active hepatitis
- Acute myocardial infarction
- Active pneumonia
- Severe systemic hypertension for age
- Acute orthopedic injury to an exercise muscle group

**Relative contraindications**

- Severe left ventricular outflow obstruction
- Severe right ventricular outflow obstruction
- Congestive heart failure
- Pulmonary vascular obstructive disease
- Severe mitral stenosis
- Ischemic coronary artery disease
- Advanced ventricular arrhythmias

diatheses, and pulmonary hypertension. In the authors’ laboratory, although there are only a few absolute contraindications to testing (principally acute disease processes involving any vital organ), providers are strongly encouraged to weigh the risk/benefit ratio of the exercise test. In other words, will the test results alter the management of the patient for whom the test itself can be life threatening? When the risk/benefit ratio is high, testing is strongly discouraged or is not performed at all.

**Laboratory equipment, staff, and procedures**

All laboratories should have basic equipment, which includes an automated blood pressure monitoring system with manual override, a cycle ergometer, a treadmill, high-quality ECG recording systems and writers, spirometers, and pulse oximeters. In most pediatric laboratories, metabolic carts with gas analyzers, which can assess ventilation and cardiac output, are typically in place. Qualified technicians, physicians, and emergency equipment and supplies in the event of respiratory or cardiac failure or life-threatening arrhythmias should be available. Personnel trained in cardiopulmonary resuscitation should be present at testing. Informed consent should be obtained before testing. The

Fig. 2. The exercising subject. The exercising subject is encouraged to wear comfortable clothing, athletic footwear, and be ready to exercise. Subjects use nonverbal signals to communicate symptoms, their level of fatigue, or their desire to terminate the test.
authors instruct subjects to wear comfortable clothing and athletic shoes and to refrain from eating or drinking for at least 2 hours before the test (Fig. 2).

Types of protocols and choice of test

The choice of treadmill testing or cycle ergometry depends on the type of information desired. The cycle ergometer has practical advantages over treadmill testing: it is less expensive to purchase and maintain, is safer, and is less intimidating to exercising subjects. One of the most important advantages of cycle ergometry is decreased artifact when measuring ECG and blood pressure data. Physical working capacity can be easily assessed with modern electronically braked cycle ergometers but is extremely difficult to assess by treadmill, because of the differences in walking or running economy by different subjects [3]. Cycle ergometry is also preferred if one needs accurate blood pressure assessment, because obtaining blood pressures from a subject running on a treadmill may be difficult, particularly at peak exercise [6–8]. If one wants to assess maximum oxygen consumption, however, treadmill testing is recommended, because in running both upper and lower limbs consume oxygen; in cycling, only the legs are involved. Historically, measurements of oxygen consumption are about 10% higher with treadmill testing than with cycle ergometry [9,10]. If the indication for the test is symptom related, one should select the protocol that is likely to provoke the symptoms. For example, if a patient has chest pain while running, the requesting physician should specify treadmill testing, because cycle ergometry may not induce symptoms. If one suspects an arrhythmia at higher heart rates, cycle ergometry is probably the better choice of test, because there is less motion artifact on the ECG. Cycle ergometry may be easier to use for patients with neuromuscular disorders [3]. The authors habitually attempt to use the protocol that is likely to give the most useful information or to answer the questions of the referring physician (Table 1).

Numerous protocols have been used in pediatrics testing. For more than 20 years, the Bruce treadmill protocol or modified Bruce protocols have been most widely used in pediatric and adolescent patients. For cycle ergometry, the authors use a ramp protocol during which continuous increases in resistance to pedaling occur at a chosen slope, with the overall goal of the subject’s achieving a work rate of approximately 3 watts/kg lean body mass by 10 minutes of exercise time. The authors have found that work loads above this level this may cause a subject to have muscle fatigue before achieving the expected peak oxygen consumption, whereas lower work rates typically have led to subject boredom. In the past, endurance time on the treadmill was thought to be an excellent surrogate for cardiovascular fitness (ie, individuals who are more fit have longer exercise durations). Using treadmill endurance times as a measure of fitness, however, assumes that subjects have nearly equal capability to run on a treadmill, which may not be the case. Furthermore, given the marked variability in protocols used in different laboratories, endurance time is probably not the ideal research tool.
Caution regarding the use of endurance time as a surrogate for cardiovascular fitness has been suggested by other investigators [3]. The easiest and most reproducible measurement of cardiovascular fitness is oxygen consumption. Given the availability of equipment to assess oxygen consumption, treadmill endurance times are likely not to be considered helpful in the future.

Assessment of aerobic fitness

Assessing aerobic fitness has been the topic of many publications. Space does not allow an in-depth analysis of how fitness is assessed. Numerous studies have examined heart rate, ratings of perceived exertion by the subject or examiner, oxygen consumption, working capacity, and endurance times, alone or in combination, as a way of assessing whether the test was maximally strenuous. The advantages and disadvantages of these indices are discussed briefly here, and then the authors discuss their approach to this subject.

Heart rate

Peak heart rate has been traditionally used as a marker of exercise effort because, with some exceptions, heart rate is linearly related to work intensity [3]. Most laboratories use the formula 220 − age in years as a target heart rate,
because this equation fits well in exercising adults. Although some literature suggests that this equation may not fit precisely in children [11], the authors have found this formula useful and easy to remember. The authors believe that if a subject can achieve 90% of the target heart rate, an acceptable maximum effort has likely been made. The exception to this rule occurs when a subject has either chronotropic impairment or is taking β-blockers. In these cases, other methods must be used to assess exercise effort.

_Pulmonary function studies, breathing reserve, and the respiratory exchange ratio_

Resting pulmonary function studies include assessment of forced vital capacity and forced expiratory volumes during the early (forced expiratory volume at 1 second, FEV₁) and middle (forced expiratory flow, midexpiratory phase, FEF₂₅%–₇₅%) phases of exhalation. In some cases the peak expiratory force is also assessed. The value of these studies is to determine the presence of restrictive or obstructive lung mechanics at rest. Most laboratories also assess the maximal voluntary ventilation (MVV) at rest. The subject is asked to breathe deeply and quickly for 10 to 15 seconds, and the amount of air moved is extrapolated to obtain a volume of air exhaled over an entire minute (performing this maneuver for longer than 15 seconds will probably cause lightheadedness and may lead to fainting). This volume represents the theoretical maximal minute ventilation (VE) the subject may attain. This volume of air is then compared with the VE at peak exercise. Because in most patients ventilation is not the rate-limiting step in exercise performance, nearly all patients will have a breathing reserve still available at the conclusion of exercise. The breathing reserve, expressed as a percentage, is calculated by the equation

\[
\text{Breathing reserve} = \frac{1}{\text{MVV} / \text{VE}}
\]

Breathing reserves in excess of 50% are seen in patients who give a submaximal effort. Lower breathing reserves typically are seen in athletic individuals who give excellent efforts but can also be seen in patients who have pulmonary disorders and exhaust their lung capabilities.

The respiratory exchange ratio (the ratio of carbon dioxide excreted relative to uptake of oxygen) is also helpful in assessing effort. Typically this ratio at rest approximates 0.8 but can be slightly different depending on the diet. At peak exercise, values are typically around 1.2, indicating that a patient is excreting significantly higher amounts of carbon dioxide at peak exercise. This excretion correlates with the clearance of this gas from the lungs after it has been removed from working muscle as a by-product of aerobic metabolism and the buffering of lactic acid by bicarbonate in the blood as a consequence of anaerobic metabolism. Higher respiratory exchange ratios at peak exercise typically indicate an excellent effort, whereas ratios less than or approximating 1.1 may indicate a submaximal effort.

In some individuals, peak heart rate, breathing reserve, oxygen consumption at anaerobic threshold, and peak respiratory exchange ratio must all be assessed to evaluate effort.
Aerobic capacity and the anaerobic threshold

Aerobic capacity, assessed by measuring the peak consumption of oxygen with gas analysis, is similar in prepubescent girls and boys (Table 2). Significant differences emerge during and after puberty, however. In boys, because of higher muscle masses, peak oxygen consumption increases by about 20%. Teenage girls have no increase and, because of higher amounts of adipose tissue/kg body mass, may actually have lower oxygen consumption/kg body mass than preadolescent girls.

Maximal oxygen consumption is defined as the highest oxygen consumption achieved during a maximal or supramaximal exercise test. During a graded exercise test, adult subjects often show a plateauing effect for oxygen consumption at the highest work rates. The oxygen consumption remains constant despite a continued rise in the work rate. This plateau value is the maximal oxygen consumption. In children this phenomenon is seldom observed. Failure to achieve this response should not be misconstrued as failure to achieve a maximal oxygen consumption.

The ventilatory anaerobic threshold is defined as the level of oxygen consumption at which the minute ventilation and minute carbon dioxide production begin to rise out of proportion to the rise in oxygen consumption. This rise results from the recruitment of highly glycolytic type II muscle fibers and the resultant production and subsequent buffering of lactic acid. In healthy children and adolescents the ventilatory anaerobic threshold normally occurs at 55% to 65% of the maximal oxygen consumption. Because the ventilatory anaerobic threshold is a submaximal measurement, it is relatively independent of effort and may be useful when the measurement of maximal oxygen consumption is difficult.

Physical working capacity

The typical maximal working rate on the cycle ergometer in one study published 13 years ago was 3.5 watts/kg for boys and 3 watts/kg for girls [12]. Although the authors have not formally analyzed their recent data, the trend in their laboratory is for mean values slightly lower than those reported in this study.

Table 2
Normal values for aerobic capacity in children and adolescents using cycle ergometry

<table>
<thead>
<tr>
<th></th>
<th>Boys</th>
<th>Girls</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>≤13 year</td>
<td>&gt;13 year</td>
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<tr>
<td>Maximal VO₂ (mL/kg/minute ± SD)</td>
<td>42 ± 6</td>
<td>50 ± 8</td>
</tr>
<tr>
<td>VO₂ at VAT (mL/kg/minute ± SD)</td>
<td>26 ± 5</td>
<td>27 ± 6</td>
</tr>
<tr>
<td>VO₂ at VAT/Maximal VO₂ (%)</td>
<td>54 ± 6</td>
<td>55 ± 10</td>
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Abbreviations: VAT, ventilatory anaerobic threshold; VO₂, minute oxygen consumption.
ECG monitoring

ECG monitoring of the exercising patient provides a precise measurement of the heart rate response to the exercise load and is an indirect measure of the adequacy of effort [3]. The ECG is useful in assessing the presence of exercise-induced arrhythmia and ischemia. It is useful in ruling out the presence of significant cardiac disease in patients who have noncardiac chest pain during exercise.

Terminating the test

Termination of the stress test in the authors’ laboratory at The Children’s Hospital of Philadelphia is variable and protocol dependent. In the protocol the authors use to assess for the presence of exercise-induced asthma, the test is terminated at the 6-minute mark (typically, the child’s or adolescent’s heart rate approximates 180 beats/minute). If the patient is performing a maximally strenuous test, then the test is terminated by the patient but can be terminated by the technician or testing physician if there is evidence of potential hazard to the patient (Box 3). The authors monitor a recovery period of 10 minutes, with the first few minutes spent slowly pedaling against no resistance or walking slowly on the treadmill.

Box 3. Indications to terminate an exercise test

Patient requests termination
Diagnostic criteria for the test are met
Equipment failure
Chest pain*
Dizziness, headache*
Syncope
Severe dyspnea*
Advanced arrhythmias or progressive atrioventricular block
ST segment depression greater than 3 mm
Systolic blood pressure greater than 250 mm Hg
Progressive drop in systolic blood pressure

* Symptoms should be evaluated with all other monitored patient information to determine if the test needs to be terminated.

Specific conditions in which exercise testing is of value

Congenital heart disease

More formal exercise studies have been performed more in children with congenital heart disease than in any other pediatric group. Exercise testing in patients with congenital lesions can aid the decision-making process as to whether an intervention such as surgery is needed or can help in assessing the success of an intervention.

Unrepaired congenital cardiac lesions

Aortic stenosis or aortic insufficiency. Left-sided obstructive lesions, including aortic stenosis, have been the subject of numerous studies and are a common reason for referral for stress testing. The exercise test should evaluate the presence of subendocardial ischemia manifested by ECG changes in the ST segments and T waves. A blunted rise in systolic blood pressure may occur in severe cases. Results of exercise testing alone are seldom a definitive reason for surgical intervention but may be useful as part of an overall assessment of the severity of the outflow obstruction.

Surgically repaired congenital heart disease

Transposition of the great arteries. Two types of surgical repairs are used for transposition of the great arteries. The atrial switch operation (Mustard or Senning) was widely used during the 1960s and 1970s, but atrial arrhythmias, diminished right-heart function, chronotropic impairment, and reduced exercise performance have been reported [13]. Improvements in surgical technique and postsurgical management resulted in the successful arterial switch operation in the early 1980s, and this procedure remains the procedure of choice today. Both physical working and aerobic capacities are significantly superior in patients treated with the arterial switch operation than in patients who have undergone the atrial switch operation [13,14]. Unlike atrial switch patients, arterial switch patients, as a whole, have normal oxygen consumption and maximal cardiac indices as compared with healthy subjects [15]. It is not yet known whether the potential problems associated with transplanted coronary arteries, which is part of the arterial switch procedure, will develop in this group of patients. Published studies indicate an approximately 10% incidence of exercise-induced ischemic changes in arterial switch patients [15].

Tetralogy of Fallot. Before 1990, most studies of exercise performance in patients with tetralogy of Fallot found mild to moderate reduction of aerobic capacity compared with normal subjects [16–24]. In the small subset of patients born with tetralogy of Fallot with absent pulmonary valve syndrome, marked enlargement of the proximal pulmonary arteries results in bronchial compression, symptoms of airway obstruction, and recurrent pulmonary infection. Formal studies in these patients also show reduced aerobic and physical working
capacities compared with normal subjects. The patients with absent valve syndrome who had successful surgical repairs showed no significant differences compared with patients with pulmonary stenosis who had transannular patches [16]. In the current era, however, one study found these patients to have nearly normal physical working and aerobic capacities [25]. Free pulmonary insufficiency and right ventricular dilation seem to be key factors in limiting aerobic capacity in this population.

**Repair of anomalous coronary arteries.** Paridon et al [26] found no significant differences in work rate or oxygen consumption between patients with anomalous left coronary artery when the repair was performed at less than 2 years of age and patients with repairs performed after infancy. Exercise was frequently associated with ECG evidence of abnormal myocardial perfusion, and perfusion defects were occasionally noted by myocardial radionuclide imaging. The clinical significance of these findings is unknown at this time.

**Fontan physiology.** In single-ventricle or Fontan physiology, blood flows passively from the vena cavae to the lungs without benefit of a pump. Venous return from the lungs is pumped to the body by the systemic ventricle (either an anatomic right or left ventricle). This surgically constructed physiology, although not optimal, has resulted in the survival of many patients who otherwise would have died from severe congenital heart malformations. Numerous studies have demonstrated that these patients uniformly have diminished physical working and aerobic capacities, chronotropic impairment, reduced stroke volume, intracardiac and intrapulmonary shunting, and abnormal pulmonary mechanics [27–33]. Important work in the field of exercise physiology has influenced the timing of surgical intervention. A decade ago, it was common for the Fontan procedure to be delayed until the age of 3 or 4 years or beyond. Work at a number of institutions showed that exercise capacity is higher when the systemic ventricle is volume unloaded at an earlier age [34,35]. It is now common for an early intermediate procedure (bidirectional Glenn) to be performed in infancy and for the Fontan procedure to be completed by age 2 or 3 years. As previously stated, heart rate responses are crucial for exercise, and efforts have been made to increase the peak heart rates in these patients with rate-responsive pacemakers. Despite improved chronotropic responses from rate-responsive pacemakers, physical working and aerobic capacities did not increase significantly [36,37]. In patients with failing Fontan physiology, however, improvement in nearly all indices of exercise performance has been seen after combined right atrial reduction, maze procedure, and pacemaker implantation [38–40].

**Coarctation of the aorta.** Residual coarctation is common in patients who have had repair of coarctation of the aorta. Previous studies have found that a significant residual coarctation may be unmasked during exercise testing when significant systolic hypertension occurs during exercise. Other investigators
noted significant residual lesions were found at cardiac catheterization when the
exercise study before the catheterization uncovered an elevated upper to lower
extremity systolic gradient during recovery.

Patients with residual coarctation and systolic or diastolic hypertension at peak
exercise had significantly higher plasma norepinephrine and renin concentrations
at peak exercise and during recovery. These augmented sympathetic nervous
system and renal responses to exercise may contribute to the development of
chronic hypertension in these patients [41].

Total anomalous pulmonary venous connection. Patients who have undergone
corrective procedures for total anomalous pulmonary venous connection and who
have no residual lesions have been shown to have mildly reduced aerobic
capacity and mild chronotropic impairment. Although these patients also have
evidence of mild restrictive mechanics on formal pulmonary function testing,
breathing does not seem to compromise their performance [42].

Acquired heart disease

Kawasaki syndrome

Kawasaki syndrome, an inflammatory condition affecting the coronary ar-
teries, has been the subject of much work because of the effect that this illness
during childhood may have on patients when they are adults. The authors
routinely perform exercise studies on patients long after the acute illness has
resolved to help with risk assessment. Paridon [43] found that patients with
residual coronary artery lesions had regional blood flow abnormalities during
exercise. Although no patients in this study had ECG evidence of ischemia,
radiouclide imaging with technetium was abnormal in 60% of the study
participants. Furthermore, quantitative blood flow analysis using positron
emission tomographic analysis showed that patients with Kawasaki disease
without ECG evidence of coronary arterial abnormalities had abnormal responses
to adenosine stress testing, with evidence of reduced myocardial blood flows,
reduced myocardial blood flow reserve, and higher total coronary resistance
compared with healthy adult volunteers [44]. The clinical significance of this
information is not yet known. Despite these abnormal laboratory findings,
maximal oxygen consumption is normal after Kawasaki disease, regardless of
coronary artery status [45].

Arrhythmias

Long QT syndrome

In normal persons, the QT interval shortens with exercise [46], but the
corrected QT interval (QTc) changes very little. In patients with long QT
syndrome the QTc may even prolong during intense work, potentially leading to a
life-threatening dysrhythmia. A formal exercise test may therefore be useful in
helping to exclude long QT syndrome in selected patients. The authors have found
that the test, although not always diagnostic, can be used as additional data when attempting to stratify risks for certain patients. Also, the morphology of the T wave at rest, during exercise, and in recovery may be of diagnostic value [47,48].

Heart transplant recipients

Published studies on formal exercise testing in pediatric heart transplant recipients are sparse. The few published studies found that these heart transplant recipients had reduced physical working and aerobic capacities and chronotropic impairment [49–51]. Squires et al [52] reported the results of a supervised exercise rehabilitation program in adult transplant recipients who exercised on a regular basis for 6 to 8 weeks. In these patients, there was evidence of physiologic re-innervation of the transplanted heart resulting in higher peak heart rates than in other transplant recipients. Despite higher heart rates at peak exercise, there was no significant improvement in the aerobic capacity in this cohort. At The Children’s Hospital of Philadelphia, transplant recipients are provided with an optional exercise rehabilitation prescription, under the auspices of a trained exercise physiologist. This program includes dynamic and isometric activities. The long-term results of such a program in pediatric patients are under investigation.

Noncardiac illnesses

Survivors of childhood cancers

Anthracycline-induced cardiomyopathy, a long-recognized problem in children who survive childhood cancers, causes a reduction in physical working and aerobic capacities. Hogarty et al [53] have described impaired cardiovascular responses to exercise following bone marrow transplantation. In this group of patients, working rate may improve with time. The use of routine afterload reduction does not seem to alter the indices of exercise performance in these patients [54]. Systematic evaluation of these patients by serial exercise studies may be of value in identifying those who have cardiovascular impairment as well as in implementing rehabilitation therapy.

Systemic hypertension

In 1979 Riopel [55] reported blood pressure responses from a large group of healthy children. This study found gender and race differences in blood pressure responses to treadmill testing. Progressively higher systolic values correlated with higher body surface areas, whereas diastolic blood pressures remained unchanged or decreased slightly during exercise Alpert and others [56,57] at the Medical College of Georgia found differences in systolic pressures between black children and white children during cycle ergometer testing. The implication of these findings is not entirely clear, but some investigators have postulated a possible linkage of the value of the systolic pressure response during exercise in childhood and the later development of systemic hypertension during adulthood [57].
Wanne and Haapoja [58] found consistent differences in blood pressure responses between boys and girls, with the highest blood pressures seen in postpubertal boys. In most of these and other studies, systolic blood pressure values in excess of 240 mm Hg were rare. The reader is referred to the tables and figures found in these publications for assistance in assessing an abnormal response to graded exercise. In the authors’ laboratory, an exercise test is not terminated unless the systolic blood pressure exceeds 250 mm Hg.

Most exercise physiologists agree that, despite the occurrence of systolic hypertension during exercise, regular aerobic exercise has beneficial effects in lowering resting blood pressures [1,59]. There are no large studies suggesting that regular exercise is harmful to hypertensive youth. The authors therefore encourage these patients to exercise on a regular basis.

**Exercise-induced asthma**

The prevalence of asthma and exercise-induced asthma is increasing worldwide, and assessment for this condition is a common reason for referral to the authors’ laboratory. In a recent review in this journal, Sheth [60] reported that exercise-induced asthma occurs in 70% to 90% of patients with persistent asthma and in about 10% of the general population. Exercise-induced asthma is defined as “transient narrowing of the airway that follows vigorous exercise” [61]. In healthy individuals the fall in FEV1 with exercise is usually less than 5%, but in exercise-induced asthma the fall in FEV1 with exercise is between 10% and 15%. This drop in lung function may manifest as cough, shortness of breath, wheeze, or inability to perform physical activities and exercise [60]. The authors’ protocol, which consists of rapidly increasing the treadmill speed and grade so that the patient is running at nearly maximal capacity for approximately 6 minutes, is designed to provoke bronchospasm in predisposed subjects. Pretest and posttest pulmonary function studies and flow volume loops during the study are analyzed by pulmonologists, who work jointly with the cardiologists in the assessment of these patients. Significant decreases in pulmonary function as a result of the exercise are treated with bronchodilators, and repeat pulmonary function studies are performed. A laboratory equipped to provide this service offers a valuable tool to practicing pediatricians, pulmonologists, and allergists by assisting in establishing or ruling out this diagnosis and by assessing the presence of adequate control in treated patients. With appropriate therapy, children with exercise-induced asthma should be able to participate in sports and maintain normal activity [60].

**Cystic fibrosis**

Some studies of children with cystic fibrosis have demonstrated low physical working and aerobic capacities as well as low pulmonary reserves in these children [62,63]. New data from the authors’ laboratory from a population of 65 children and adolescents confirmed the intuitive notion that there is a positive correlation between lean body mass, pulmonary function, and exercise performance. Ongoing work at The Children’s Hospital of Philadelphia is exploring ways
to improve the functional capacity of these patients. These methods may ultimately include active supervised physical rehabilitation programs and improved nutritional support.

Summary

State-of-the-art stress testing laboratories can provide a myriad of useful physiologic data on patients with congenital malformations or suspected of having acquired disorders. Unlike most medical tests, which are performed on resting subjects, exercise stress testing can assess the functional capacity of the individual and can provide a more complete understanding of the patient’s physical abilities and limitations.

References


