AHA Medical/Scientific Statement

Special Report

Guidelines for Exercise Testing in the Pediatric Age Group

From the Committee on Atherosclerosis and Hypertension in Children, Council on Cardiovascular Disease in the Young, the American Heart Association

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The purpose of this report is to update guidelines for exercise testing in both normal children and children with cardiovascular disease. This report is intended for physicians, nurses, exercise specialists, physical educators, technologists, and other health professionals involved in the exercise testing and training of children. These standards and guidelines are intended to complement the American Heart Association’s adult exercise testing standards as well as to supplement and update an earlier publication of the AHA on exercise testing in children.

Because exercise is only one of many stresses to which humans can be exposed, we prefer the term “exercise test” to “stress test.” Exercise can be useful as a physiological stress to elicit findings and abnormalities that are not evident at rest. This report emphasizes exercise laboratory testing and does not attempt to address the uses of exercise in physical education classes or other nonlaboratory settings. But because laboratory exercise testing may not reproduce the stress of a specific sport or activity, evaluation may need to be tailored for individuals who report the occurrence of symptoms during specific sports.

Basic Exercise Physiology

An understanding of the physiological changes that occur during exercise is of practical importance to the clinician who performs exercise testing of children. In particular, the physiological adaptations of normal children to exercise provide insight into the abnormalities found at rest in children with congestive heart failure. Because obtaining useful and accurate laboratory measurements and interpreting test results depend on an appreciation of normal physiological responses, this section provides an overview of the terminology and measurements used in the exercise testing of children that have come from the field of exercise physiology.

Work

Exercise is defined as any activity involving the generation of force by activated muscle(s) that results in an alteration of the homeostatic state. In dynamic exercise, the muscle may perform shortening (concentric contractions) or be overcome by external resistance and perform lengthening (eccentric contractions). When muscle force results in no movement, the contraction is termed static or isometric. Static exercise (eg, hand grip) imposes a relatively greater pressure-load than volume-load on the heart; dynamic exercise (eg, running) results primarily in a volume-load. The cardiovascular response is proportional to the intensity of dynamic exercise up to maximal levels of exercise. Dynamic exercise is preferred for most testing because it can elicit maximal or near-maximal cardiovascular and metabolic responses. With isometric exercise, in contrast, the subject is more likely to be limited by acute muscular fatigue before cardiac limitations are approached. Most activities combine varying amounts of both isometric and dynamic exercise. Estimates of the amount of exercise performed are made by using the following definitions.

Work. Force expressed through a distance but with no limitation on time. The units for work are joules or kilopond*meter.

Power. The rate of performing work, ie, the derivative of work with respect to time or the product of force and velocity. The units for power are unit of work per unit of time. One joule per second equals one watt. Kilopond*meter per minute is also used to express power.

Maximal power output. The highest rate of work achieved during exercise testing.
Endurance time. The total test time to exhaustion for an individual performing a continuous graded test. The duration of testing is compared with the endurance time obtained by normal subjects matched for age and gender who were tested by using an identical protocol.

Physiological working capacity—70 (PWC-70). The highest rate of submaximal steady-state work corresponding to a heart rate of 170 beats per minute identified during continuous graded cycle ergometry.

Total work. Accumulated work to exhaustion or to a predetermined end point during exercise testing.

The units of work have traditionally varied with the type of ergometer used during the test. With the use of a cycle ergometer the units of work are expressed as watts or joules, whereas units of kilopond • meter/minute are typically used to express work with treadmill testing.

The expected amount of work performed during a particular test varies with the age, gender, and fitness of the subject and the type of protocol used.

Perceived Exertion

The subjective rating of intensity of perceived exertion by the person exercising is a good indicator of relative fatigue and is used in conjunction with the heart rate. The concept of perceived exertion has been interpreted to quantify effort during exercise.3 A 6- to 20-point Borg scale may be used to assess perceived exertion.4

Special verbal and written instructions about the rating of perceived exertion are provided to the test subject. Although perceived exertion varies among children at given rates of work, results are reproducible from test to test. The Borg scale may be used in judging the degree of fatigue reached from test to test performed by the same child or to compare the level of fatigue during testing with that experienced during daily activities or training.

Heart Rate

The immediate response of the cardiovascular system to exercise is an increase in heart rate due to a decrease in vagal tone. This response is followed by an increase in sympathetic outflow to the heart and systemic blood vessels. During dynamic exercise, the heart rate increases linearly with the rate of work. During low to moderate levels of exercise at a constant work rate, the heart rate reaches a steady state within 1 minute and increases proportional to the rate of work in subjects with a normal sinus node. Variables that affect heart rate during exercise include the type of exercise, body position during testing, gender, state of health and fitness of the subject, and environmental conditions (such as heat, cold, humidity, or altitude).

Young children compensate for a smaller heart and lower stroke volume by an increased heart rate at a given rate of work; thus, they attain higher maximal heart rates than adults. After puberty, maximal heart rate decreases with age at a rate of 0.7 or 0.8 beats per minute per year of age. Females have a higher heart rate than males at any given rate of work after puberty. Obese children have higher submaximal heart rates than lean children at the same rate of work. Exercise in a hot or humid climate results in higher heart rates for a given rate of work than exercise in a neutral thermal environment.

A decrease in resting heart rate is characteristic of conditioning. Peak rate that can be achieved by the sinus node is largely independent of the state of condition. Increased mechanical efficiency with retesting may provide an increased intensity of exercise that raises the observed peak heart rate at maximal voluntary effort. The peak heart rate observed may decrease on subsequent tests with endurance training in those with initial high maximal heart rates. Heart rate alone is an inadequate determinant of fitness. Additional physiological determinants to assess the level of conditioning may include peak oxygen consumption, the anaerobic threshold, endurance time, and total work.

Motivational factors, subject cooperation, mechanical efficiency, and the type of protocol are also important determinants of heart rate with exercise testing. Treadmill exercise results in a slightly higher maximal heart rate than does cycle ergometry. Table 1 gives examples of peak heart rates in children of various ages using either treadmill or cycle.

Electrocardiographic Changes

Electrocardiographic changes during ventricular repolarization have been used to identify mismatch of myocardial oxygen demand and supply.

Investigators differ in their analyses and interpretation of ST segment changes on exercise electrocardiography.20 Fig 1 illustrates two methods of measuring the depression of the ST segment and the J point. In the upper panel, the baseline (P-R isoelectric line) is superimposed on the P-R segment of the QRS-T complex for identifying the J-point depression. In the lower panel, the baseline is drawn connecting several P-Q points of at least three consecutive QRS-T segments for identifying the J-point and ST depression. The criteria for significant ST-segment J-point depression include a J-point depression ≥2 mm and an ST depression >1 mm with a flat or downsloping ST segment at 60 milliseconds.

Normal physiological J-point depression was found in 9% of boys and 18% of girls with the PQ-PQ isoelectric line method and 2.3% of boys or girls in the same study by using the PR isoelectric line method.21 The ST segment in normal subjects with “physiological” ST depression rapidly returns to baseline (within 80 milliseconds) and is not flat or downsloping (Fig 2).

Interpretations of abnormal repolarization are impossible if depolarization is also abnormal. Bundle branch block, which is often present in children who have heart disease, renders the ST segments uninterpretable with exercise testing. This is also true with a ventricular pacemaker or with Wolff-Parkinson-White syndrome.

Cardiac Output and Stroke Volume

Cardiac output (CO) is the product of stroke volume (SV) and heart rate (HR). The relation is as follows:

\[ CO = SV \times HR \]

Stroke volume depends on preload, afterload, and contractility.

Cardiac output increases in an almost linear manner during exercise, concomitant with increasing oxygen consumption, increasing at each higher exercise level during a graded test. A steady-state cardiac output is achieved in normal children within 2 to 3 minutes of
TABLE 1. Maximal Heart Rate With Treadmill, Cycle Ergometer, and Supine Cycle

<table>
<thead>
<tr>
<th>Author, Year</th>
<th>Age, y</th>
<th>Population</th>
<th>Sex</th>
<th>Peak HR, bpm</th>
<th>Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Treadmill</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Shephard, 1969⁵</td>
<td>11-13</td>
<td>Canada</td>
<td>Both</td>
<td>193</td>
<td>Continuous, progressive</td>
</tr>
<tr>
<td>Skinner, 1971⁶</td>
<td>6-15</td>
<td>USA</td>
<td>Male</td>
<td>197.7-200.9</td>
<td>Continuous, progressive</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>203.0-203.5</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Male</td>
<td>199.1</td>
<td>Intermittent, multistage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>202.7</td>
<td></td>
</tr>
<tr>
<td>Hermansen, 1971⁷</td>
<td>10-12</td>
<td>Scandinavia</td>
<td>Male</td>
<td>205.9-206.6</td>
<td></td>
</tr>
<tr>
<td>Wilmore, 1974⁸</td>
<td>8-12</td>
<td>USA</td>
<td>Male</td>
<td>196.8±7.7 (177-213)</td>
<td></td>
</tr>
<tr>
<td>Wilmore, 1982⁹</td>
<td>13-15</td>
<td>Male</td>
<td>202.1±8.5 (173-222)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cumming, 1978¹⁰</td>
<td>4-18</td>
<td>Canada</td>
<td>Both</td>
<td>193-206</td>
<td>Bruce</td>
</tr>
<tr>
<td>Riopel, 1979¹¹</td>
<td>4-21</td>
<td>USA, black</td>
<td>Male</td>
<td>179-186</td>
<td>Balke, modifications of Austin</td>
</tr>
<tr>
<td></td>
<td></td>
<td>USA, white</td>
<td>Male</td>
<td>183-192</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Female</td>
<td>181-194</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>187-191</td>
<td></td>
</tr>
<tr>
<td>Cycle Ergometer</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Astrand, 1952¹²</td>
<td>7-9</td>
<td>Scandinavia</td>
<td>Male</td>
<td>208</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>211</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Male</td>
<td>211</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>209</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Male</td>
<td>205</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>207</td>
<td></td>
</tr>
<tr>
<td>Goldberg, 1966¹³</td>
<td>6-16</td>
<td>USA</td>
<td>Male</td>
<td>194±9</td>
<td>Continuous</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>193±8</td>
<td></td>
</tr>
<tr>
<td>Wilmore, 1967¹⁴</td>
<td>7-9</td>
<td>USA</td>
<td>Female</td>
<td>195</td>
<td>Intermittent, multistage</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>196</td>
<td></td>
</tr>
<tr>
<td>Ericksson, 1971¹⁵</td>
<td>6-15</td>
<td>Scandinavia</td>
<td>Male</td>
<td>200.5±2.9</td>
<td>Continuous</td>
</tr>
<tr>
<td>James, 1980¹⁶</td>
<td>5-33</td>
<td>USA, 95% white, 5% black</td>
<td>Both</td>
<td>187-199</td>
<td>Continuous, progressive,</td>
</tr>
<tr>
<td></td>
<td>(mean, 14.3)</td>
<td></td>
<td></td>
<td></td>
<td>Constant workload,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>electrically braked</td>
</tr>
<tr>
<td>Alpert, 1982¹⁷</td>
<td>6-15</td>
<td>USA, Black</td>
<td>Male</td>
<td>188-194</td>
<td>Continuous, graded</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>185-195</td>
<td>Mechanically braked</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Male</td>
<td>191-194</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>191-195</td>
<td></td>
</tr>
<tr>
<td>Supine Cycle</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cumming, 1977¹⁸</td>
<td>5-16</td>
<td>Canada</td>
<td>Male</td>
<td>170±17</td>
<td>Intermittent, graded</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Female</td>
<td>174±11</td>
<td></td>
</tr>
<tr>
<td>Lock, 1978¹⁹</td>
<td>5-16</td>
<td>USA</td>
<td>Both</td>
<td>142±4.9</td>
<td>Fixed rate of work,</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>submaximal</td>
</tr>
</tbody>
</table>

HR indicates heart rate; bpm, beats per minute.

Each rate of work increase,⁶,²² usually cardiac output shows a threefold through fivefold increase from rest to maximal exercise, as illustrated in Table 2. Children typically have a markedly lower stroke volume because of smaller body size, but information is limited. Table 3 provides values for stroke volume derived from five studies of healthy children performing either supine or sitting exercise using a cycle ergometer. The cardiac output in a given individual depends on the type of exercise being performed. Upright exercise
A lack of increase or a decrease in systolic blood pressure below the normal resting level has been widely held as an ominous indication of severe cardiac dysfunction. A decrease in blood pressure during exercise occurs when the peripheral vascular resistance drops normally but a cardiac abnormality limits the subject's ability to increase cardiac output with exercise. This may occur with severe aortic stenosis or cardiomyopathy. An exertional drop in blood pressure is, however, not as specific as once thought and can occur in normal individuals.

Systolic blood pressure increases with progressive workloads. In adults, a maximal exercise systolic pressure above 220 mm Hg has been considered an excessive rise. Maximal systolic blood pressure in children rarely exceeds 200 mm Hg, and there is no evidence of danger when the systolic blood pressure reaches the 250–mm Hg range during exercise in an asymptomatic child or adolescent. For optimal safety of the exercise testing procedure, however, the systolic blood pressure generally should not be permitted to exceed a range that can be measured during the test.

The normal diastolic blood pressure response to exercise in children is not known with confidence because ambient noise and movement of the child's arm during an exercise study make the response difficult to...
determine accurately. This is generally a more difficult problem with treadmill testing than with cycle ergometry. However, it is unusual for children exercising on a treadmill to have a significant increase in diastolic pressure.

The magnitude of increase of peak systolic and diastolic blood pressure values during exercise increases with age and body size. Because males have a higher maximal stroke volume than females, they routinely have a higher systolic blood pressure response.

**Oxygen Consumption**

Oxygen uptake (\(\text{VO}_2\)) increases rapidly when dynamic exercise begins. After the second minute at each level of intensity of exercise, oxygen uptake usually reaches a plateau. In a steady state at a given workload, heart rate, cardiac output, blood pressure, and pulmonary ventilation are maintained at reasonably constant levels.

The maximum oxygen uptake (\(\text{VO}_2\text{max}\)) is the highest amount of oxygen that a given individual can consume while performing dynamic exercise; in contrast, peak oxygen consumption is the maximal amount of oxygen uptake observed during a specific exercise study. Peak oxygen consumption may or may not equal maximum oxygen uptake.

In adults, \(\text{VO}_2\) reaches a plateau at \(\text{VO}_2\text{max}\) and no further increase is observed with further increases in the rate of work. This plateau is infrequently found when testing children, and \(\text{VO}_2\text{max}\) cannot be precisely determined in many pediatric studies; thus, the peak observed oxygen uptake is used instead.

Children increase their oxygen consumption approximately 10-fold during exercise; adults typically obtain a 10- to 15-fold increase. A trained athlete may achieve as much as a 20-fold increase in oxygen consumption. Oxygen consumption is strongly related to fat-free body mass, and when \(\text{VO}_2\) is indexed by body weight, the difference in oxygen consumption between genders becomes minimal.

Table 4 lists ranges for peak oxygen consumption measured in normal children using a variety of exercise test protocols; these are reviewed in detail by Freedson and Goodman.

**Ventilatory Anaerobic Threshold**

The ventilatory anaerobic threshold (VAT) is a laboratory measurement that approximates an identification of the point at which the subject's oxygen supply begins to be outstripped by demand during an exercise test. In normal individuals, a maximal aerobic exercise effort is reached when the cardiovascular system has attained its maximal capacity to deliver blood to exercising muscles, and cardiac output can increase no further. Increasing peripheral oxygen extraction occurs and raises the difference between systemic arterial and venous oxygen content. As the limit of tissue oxygen delivery is reached, additional energy is provided anaerobically by glycolysis, which results in a rise in muscle and plasma lactic acid.

The anaerobic threshold is a theoretical point that occurs during dynamic exercise when the muscle uses anaerobic metabolism as an additional source of energy. A rise in tissue lactate level slightly precedes the rise in blood lactate level. All tissues do not shift simultaneously to anaerobic metabolism, so that this “point” in time is actually a brief interval during the test in which exercising tissues change from predominantly aerobic metabolism to anaerobic metabolism.

Lactate concentration in the blood results from a dynamic relation between lactate production and lactate clearance. If blood samples are obtained throughout exercise testing and lactate concentration is measured, at an observable point the blood lactate level

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**Table 2. Exercise Cardiac Output**

<table>
<thead>
<tr>
<th>Author, Year</th>
<th>Age, y</th>
<th>Rest Value</th>
<th>Maximum Value</th>
<th>Instrument</th>
<th>Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ericksson, 1971&lt;sup&gt;15&lt;/sup&gt;</td>
<td>13-14</td>
<td>5.25±0.50 L/min/m²</td>
<td>17.41±0.88 L/min/m²</td>
<td>Cycle</td>
<td>Continuous</td>
</tr>
<tr>
<td>Ericksson, 1973&lt;sup&gt;23&lt;/sup&gt;</td>
<td>11-13</td>
<td>3.9 L/min/m²</td>
<td>12.5 L/min/m²</td>
<td>Seated cycle in catheterization laboratory</td>
<td>Continuous</td>
</tr>
</tbody>
</table>

**Table 3. Exercise Stroke Volume in Children With Young Adult Values Included for Comparison**

<table>
<thead>
<tr>
<th>Author, Year</th>
<th>Age, y</th>
<th>Sex</th>
<th>Rest, mL/beat per m²</th>
<th>Exercise, mL/beat per m²</th>
<th>Instrument</th>
<th>Protocol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ericksson, 1971&lt;sup&gt;15&lt;/sup&gt;</td>
<td>13-14</td>
<td>Male</td>
<td>61.8±6.2</td>
<td>86.8±3.9</td>
<td>Cycle</td>
<td>Continuous</td>
</tr>
<tr>
<td>Ericksson, 1973&lt;sup&gt;23&lt;/sup&gt;</td>
<td>11-13</td>
<td>Male</td>
<td>49.4</td>
<td>66.9</td>
<td>Seated cycle in catheterization laboratory</td>
<td>Continuous</td>
</tr>
<tr>
<td>Cumming, 1977&lt;sup&gt;18&lt;/sup&gt;</td>
<td>5-16</td>
<td>Male</td>
<td>51.9±5.9</td>
<td>55.7±12.7</td>
<td>Supine cycle in catheterization laboratory</td>
<td>Intermittent, graded</td>
</tr>
<tr>
<td>Lock, 1978&lt;sup&gt;18&lt;/sup&gt;</td>
<td>5-16</td>
<td>Female</td>
<td>45.3±6.3</td>
<td>46.3±3.1</td>
<td>Supine cycle in catheterization laboratory</td>
<td>Fixed rate of work, submaximal</td>
</tr>
<tr>
<td>Astrand, 1964&lt;sup&gt;24&lt;/sup&gt;</td>
<td>Mean, 24</td>
<td>Male</td>
<td>Mean, 68</td>
<td>Mean, 57</td>
<td>Cycle</td>
<td>Continuous</td>
</tr>
<tr>
<td>Mean, 21</td>
<td>Female</td>
<td></td>
<td></td>
<td></td>
<td>Cycle</td>
<td>Continuous</td>
</tr>
</tbody>
</table>
4. Stepwise loading, Exercise in Children

Supramaximal, cycle treadmill increases above abruptly.

VAT, heart hyperventilation.

Co2 increases.

Routine blood lactate measurement is impractical in exercise testing of children. As lactate is formed, it is buffered in the serum by the bicarbonate system, and CO2 increases. This accumulation of CO2 results in reflex hyperventilation. The onset of reflex hyperventilation, or VAT, may be described as a point in time during the exercise study or can be expressed in terms of other exercise test measurements, such as percent of VO2max, heart rate at VAT, or percent of total exercise time.

The VAT has been proposed as a more sensitive marker of fitness than oxygen consumption, heart rate, or total work in pediatric training. The heart rate at VAT has been used to determine the target heart rate for rehabilitation training.

In summary, the true anaerobic threshold at the muscle cell level, the onset of the blood lactate accumulation, and the VAT are separate but related events that occur during exercise and should not be equated with one another.

Age and Lactate Level Tolerance

Peak attainable lactate levels with exercise are higher for adults than for children. One explanation for this in the past has been the suggestion that the ability to tolerate increased serum lactate levels and to persist with exercise in the anaerobic state depends on the degree of the subject's sexual maturity. This difference was attributed to developmental limitations of the activity of key enzymes, such as phosphofructokinase, that are involved in anaerobic metabolism. However, a major subjective factor confounding the interpretation of blood lactate developmental data seems to be how willing the exercising subject is to tolerate the uncomfortable symptoms associated with fatigue. Metabolic changes associated with anaerobic metabolism, although not the blood lactate itself, will contribute to the sensation of fatigue. Subjects tolerate the discomfort associated with fatigue to different degrees. Trained adults achieve higher peak exercise lactate levels than those who are untrained, and elite adult athletes often have considerably higher peak exercise lactate levels than the typical trained adult. An alternative explanation is that adults at peak exertion can usually be coerced to tolerate higher levels of fatigue symptoms than a young child, and that symptoms of fatigue are more easily tolerated by athletes after training than by those unaccustomed to the sensation of fatigue.

Inferences regarding the developmental aspects of metabolic responses to intense exercise are, for the most part, based on cross-sectional rather than longitudinal studies.

### Testing Procedures

**Ergometers**

Exercise laboratories find varying applications for different types of ergometers. Three types of ergometers commonly used are cycles, treadmills, and arm ergometers. Both the cycle ergometer and the treadmill produce adequate, reliable, and reproducible maximal loads on the oxygen transport system for collection of diagnostic and functional information. Arm ergometers can be used by subjects for whom lower extremity exercise is difficult or impossible; from a cardiopulmonary standpoint, the intensity of stress is lower than with leg exercise. Since each ergometer has different characteristics, the selection depends on the needs of the user. There are four general considerations for choosing a particular ergometer: (1) the size of the subject; (2) the space available for the exercise laboratory; (3) the specific reason(s) for performing a given exercise test; and (4) the number of variables to be monitored and recorded during the test.

Cycle ergometers are convenient for laboratories with limited space. Mechanically braked ergometers are portable and relatively silent. The standard cycle ergometer may require minor modification for testing children under 6 years of age. The modifications include varying

<table>
<thead>
<tr>
<th>Study</th>
<th>VAT, % VO2max</th>
<th>HR at VAT</th>
<th>VO2 at VAT mL/kg per min</th>
<th>No. of Children, y</th>
</tr>
</thead>
<tbody>
<tr>
<td>Washington, 198828</td>
<td>Males, 75±13</td>
<td>169±15</td>
<td>34±7</td>
<td>151 Children, 7.5-12.5</td>
</tr>
<tr>
<td></td>
<td>Females, 71±9</td>
<td>167±16</td>
<td>30±5</td>
<td></td>
</tr>
<tr>
<td>Cooper, 198429</td>
<td>60±9</td>
<td>...</td>
<td>Males, 27±6</td>
<td>109 Children, 6-17</td>
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<td></td>
<td>...</td>
<td>...</td>
<td>Females, 19±6</td>
<td></td>
</tr>
<tr>
<td>Reybrouck, 198630</td>
<td>Males, 58-74</td>
<td>...</td>
<td>29-35</td>
<td>95 Children, 5-14</td>
</tr>
<tr>
<td></td>
<td>Females, 61-70</td>
<td>...</td>
<td>24-29</td>
<td></td>
</tr>
</tbody>
</table>

VAT indicates ventilatory anaerobic threshold; VO2max, maximum oxygen uptake; and HR, heart rate. Children's ages are given as range.
the height of the seat, the angle of the handlebar, the length of the pedal arm, and the size of the seat.

Because of the stability of the trunk and arms and the ease to access to the patient, most sequential measurements (eg, radionuclide imaging and echocardiography) during exercise testing can be made more conveniently when a cycle ergometer is used.

The mechanically braked cycle ergometer increases metabolic requirements by friction. A belt surrounding the flywheel of the ergometer is adjusted to vary the resistance against which the individual pedals. Mechanically braked cycle ergometers are less expensive than either electronically braked cycle ergometers or treadmills, but they require frequent calibration. The pedaling speed must be constant to assure an unchanged rate of work. A metronome or other regular auditory sound source is useful in maintaining pedaling frequency.

The electronically braked ergometer delivers a constant rate of work throughout a range of pedaling speeds (generally 30 through 70 rpm). This is accomplished through a feedback system that increases the resistance during slow pedaling speeds and decreases the resistance during faster pedaling speeds. This type of ergometer is more expensive and requires special equipment for calibration. The efficiency of exercise (and thus oxygen consumption) varies with pedaling rate. At very low pedaling speeds with electronically braked cycle ergometers, the braking force increases and the work becomes more isometric and less aerobic.

Treadmills are usually noisier than cycle ergometers and require a larger space and a ceiling height that is adequate to accommodate tall subjects. The mechanical efficiency of running is affected by body size and weight, gait, and length of stride. Modifications of the treadmill may include an adjustment of speed for small children who have shorter strides and should include side rails and or safety straps to prevent falling. A padded mat should be placed at the end of the treadmill for the subject’s protection. Because of the higher VO₂ obtained, some physicians prefer treadmill testing to cycle ergometry for assessing the patient undergoing a cardiac rehabilitation training program. The type of ergometer selected should be appropriate for the type of training; eg, a treadmill for a jogger and a cycle ergometer for a cyclist. A treadmill is easy to calibrate without special equipment.

The requirement for coordination between the child and the test personnel and the potential problem of movement artifacts during treadmill exercise make it technically more difficult to perform repeated measurements and specialized techniques than with a cycle. It is more difficult to obtain consistent and accurate blood pressure determinations with treadmill testing than with cycle ergometry.

**Electrocardiogram**

The heart rate can be measured manually by averaging several R-R intervals. Alternatively, the electrocardiographic signal can be processed through a tachometer, and a direct recording of the heart rate based on each R-R interval can be obtained. Many commercially available electrocardiographic units are equipped with such a tachometer.

Appropriate application of the electrocardiographic electrodes and shielding of the cables is critical for obtaining artifact-free electrocardiographic recordings. Movement artifacts occur when the electrode-electrolyte interface is mechanically disturbed, resulting in a voltage change. Electrodes for exercise testing avoid metal-to-skin contact by “floating” the electrode on an electrolyte-gel mixture to minimize artifact from muscle movement. A large contracting muscle mass between two electrodes will result in an artifact that cannot be filtered. It is occasionally necessary to move electrodes to avoid large muscle groups even though the leads are placed on the torso. Although this may require some repositioning of electrodes for optimal recordings when testing a heavily-muscled adolescent, it is usually not a major problem with testing smaller children. Silver-silver chloride electrodes have very low impedance for optimal recording of low frequency electrical phenomena and perform better than the less expensive metals that have been used to fabricate electrodes. Electrodes that are too small will have an excessively high impedance; the large adult electrodes will not provide good contact on a small child and will not stay on well. The quality of electrode adhesion, which is essential for quality recordings in children, varies among the brands available.

Skin preparation is the single most important factor in obtaining precise exercise electrocardiographic tracings from children. The epidermis possesses a layer of dead skin cells (stratum corneum) with a very high electrical resistance. The dermis itself has very low electrical resistance. Skin preparation should be done as gently as possible to avoid frightening the child. Cleaning with alcohol or acetone should be followed by gentle abrasion and removal of the stratum corneum before electrode placement. This can be done by brisk rubbing with rough cloth, fine sandpaper, emery board, skin cleaning gel containing a mild abrasive, dental drill, or commercially available electrode placement guns. Obtaining well-defined and reliable electrocardiographic recordings in exercising children is impossible without meticulous attention to skin preparation technique.

The right and left arm electrodes are placed in the right and left infraclavicular fossae. The left leg electrode is placed on the lower abdomen above the left anterior superior iliac crest. The right leg lead may or may not be used on the lower abdomen. Some laboratories place the lower limb leads higher on the torso; this higher placement is of particular value in the testing of obese children. Precordial leads V₁ through V₆ are placed in the same location as for a routine resting electrocardiogram. The individual electrodes and the electrocardiographic cable should be secured to the subject’s body to minimize artifact from movement of the cables during exercise. This may be accomplished by using a commercially available knit shirt that is custom-fit for the patient or by using tape.

At least 3 leads of the standard 12-lead electrocardiogram should be displayed or recorded continuously at baseline, during testing, and for the first 10 minutes after the completion of an exercise test. Ideally, the examiner should have the option of viewing various combinations of leads, including at least one inferior lead (standard leads II, III, or aVF), one anterior right lead (V₁ or V₂), and one lateral left lead (V₅ or V₆). A complete 12-lead electrocardiogram should be recorded.
Cardiac Output Measurement

Several techniques have been used for noninvasively measuring cardiac output during exercise.\textsuperscript{30} Caution should be used when comparing cardiac outputs measured by different techniques and in different laboratories. These measurements are sensitive to small changes in methodology and exercise protocols.

The techniques used most frequently to measure cardiac output noninvasively and without the need for radioactive materials are CO\textsubscript{2} rebreathing\textsuperscript{31} and acetylene-helium rebreathing.\textsuperscript{32} When these measurements are obtained in the gas phase, the Fick technique is termed "indirect." When using CO\textsubscript{2}, the cardiac output is measured by analysis of expired gases. Arterial PCO\textsubscript{2} can be estimated by using the end-tidal PCO\textsubscript{2}. Mixed venous content can be estimated by using a CO\textsubscript{2}-rebreathing procedure in which CO\textsubscript{2} concentration in the rebreathing bag equilibrates with the alveolar air and the mixed venous blood.

An alternate method for measuring cardiac output uses inert gases that do not interact with the blood and are thereby transported in purely physical solution rather than bound to carrier molecules such as hemoglobin. Transport of these gases is said to be "blood flow-limited." When an inert gas is introduced into the lungs at a given concentration, that concentration falls at a measurable and exponential rate as a result of the uptake of that gas by the blood flow. Commonly used gases for this technique are acetylene and nitrous oxide. Doppler echocardiography has been attempted by some exercise physiologists to assess cardiac output and provide beat-to-beat measurements of stroke volume and cardiac output.

None of these noninvasive techniques offers compelling advantages or disadvantages, and the 10% variation observable from one test to another is comparable to the variability found with invasive cardiac output determinations.\textsuperscript{31}

Oximetry

Noninvasive (ear or finger oximetry) measurement of blood oxygen saturation can be useful during exercise testing of children who have congenital heart disease to either determine the presence or absence of hypoxemia or to quantify the degree of hypoxemia during exercise. Although concerns have been raised about the reliability of this technology with exercise testing,\textsuperscript{34} there is generally good reliability of oxygen saturations measured by pulse oximetry if the oximeter heart rate tracking is acceptable during exercise.\textsuperscript{35} Normal children maintain oxygen saturations greater than 90% during maximal exercise when monitored by pulse oximetry. Desaturation (less than 90%) during exercise is considered an abnormal response and may reflect pulmonary, cardiac, or circulatory compromise. However, some elite endurance athletes can desaturate to less than 90% with intense exercise, presumably due to pulmonary ventilatory-perfusion mismatch with intense exercise.

Good surface contact of the sensor electrode is vital for accurate measurements when using oximetry during exercise testing. If finger oximetry is used, the subject must be instructed not to make a "tight fist," as this will render the measurements inaccurate.

Blood Pressure Measurement

Blood pressure can be measured indirectly by using a cuff, a sphygmomanometer, and a stethoscope to detect the Korotkoff sounds. During exercise the Korotkoff sounds often are difficult to hear. For this reason, the onset of the fifth Korotkoff phase is used to indicate diastolic blood pressure for children during exercise testing. At peak effort, however, the onset of the fifth Korotkoff phase may not be heard in some children, with sounds still audible at 0 mm Hg, which makes accurate measurement of diastolic pressure impossible. Numerous commercial electronic units have been available for measuring blood pressure during exercise testing.\textsuperscript{24} Although the accuracy of some of these devices has been documented, many of those available are inadequate for accurate blood pressure determination.

Several different cuff sizes should be available. The bladder of the cuff should completely encircle the arm and the width of the bladder should be at least two-thirds the length of the upper arm. The most common source of error in measuring blood pressure of children is the use of a cuff that is too small.

In most normal subjects systolic blood pressure declines rapidly after maximal exercise, usually reaching resting levels within 6 minutes or less. In some individuals blood pressure remains lower than pre-exercise levels for several hours. Some exercise physiologists have their subjects continue to perform low-level exercise for several minutes in the postexercise period to minimize venous pooling and resultant symptomatic hypotension. Others measure the postexercise physiological data with their patients in the supine position to minimize orthostatic symptoms caused by low venous return from blood pooling in dilated vascular beds.

Respiratory Gas Measurement

Ventilation and pulmonary gas exchange may be measured during exercise by collecting the expired gas and determining the volume and fractional concentrations of oxygen and carbon dioxide in the inspired and expired gas phases. This method yields minute ventilation, oxygen uptake, and carbon dioxide production. The respiratory gas exchange ratio (VCO\textsubscript{2}/VO\textsubscript{2}) and the oxygen ventilatory equivalent (VE/VO\textsubscript{2}) can be calculated. With the addition of flow measurement with a turbine or a pneumotachograph, the average respiratory rate and tidal volumes can be measured. These measurements are relatively simple to perform and affordable for most clinical laboratories.\textsuperscript{25,35}

Rapid gas analyzers for oxygen and carbon dioxide are now commercially available. Commercially manufactured metabolic carts with on-line computers are also available, but these must be adapted for pediatric subjects. The most common systems use the average of fractional concentration of collected gas over time or analyze the gas of each breath—the so-called "breath-by-breath technique." Care must be used to assure that the mask or mouthpiece fits properly and that there are no air leaks. Closely fitting masks may be more suitable for smaller children who do not easily tolerate a mouthpiece and nose clip.
Determining the Ventilatory Anaerobic Threshold

Several techniques have been used to determine the ventilatory anaerobic threshold (VAT), which requires the measurement of oxygen consumption and carbon dioxide production. The ventilatory equivalent for oxygen and the ventilatory equivalent for carbon dioxide are plotted against time; initially, the two ventilatory equivalents increase linearly during graded exercise testing. The VAT is that point at which the slope for the ventilatory equivalent for carbon dioxide separates from the slope for the ventilatory equivalent for oxygen. At this same point, minute ventilation also increases. Approximately 20% of individuals will not demonstrate a clear-cut VAT because of erratic breathing.27

General Principles of Exercise Testing

Reasons for Exercise Testing

Exercise testing evaluates work performance and identifies mechanisms that limit the work performance of children with cardiac and other problems. Exercise testing is performed for a variety of reasons: (1) to evaluate specific symptoms or signs that may be induced or aggravated by exercise; (2) to identify abnormal adaptive responses occurring in children with cardiac or other disorders; (3) to assess the effectiveness of specific medical and surgical treatments; (4) to estimate levels of functional capacity for and to improve the safety of vocational, recreational, and athletic recommendations; (5) to estimate prognosis; (6) to evaluate fitness levels; and (7) to establish baseline data and follow up effectiveness of cardiac rehabilitation.

A properly supervised and monitored exercise test in children can be conducted with very low risk.4,36,37 The precautions listed below will help to assure the safety of the tests.

Physical Environment

An exercise laboratory is ideally at least 500 square feet (46.4 m²) and must have adequate ventilation. An ambient temperature of 22°C through 24°C with approximately 50% humidity provides a satisfactory environment for testing. The number of people in the room, the heat generated by the equipment, and the size of the room are important considerations for optimal temperature control in the exercise laboratory. The noise level must be kept to a minimum. Smoking should be prohibited in the vicinity of the laboratory. There should be a wide exit door from the laboratory to expedite patient transport if needed.

Laboratory Staffing

At least one physician must assume the responsibility of directing the laboratory. This physician should have training both in exercise testing in general and performing exercise tests in young patients with disorders of varying severity. The director assures (1) that laboratory personnel are adequately trained in the mechanics of testing and in emergency procedures; (2) that equipment works properly; (3) that acceptable testing procedures are used; and (4) that reliable results are conveyed to the referring physician, the patient, and the family.

In most instances, after proper screening of the child, the physician may delegate the actual conduct of the exercise test to personnel who have both an understanding of the pathophysiological responses to exercise testing and expertise in emergency procedures. In other instances, the physician may elect to supervise the exercise test. Two or more competent personnel with training in pediatric cardiopulmonary resuscitation are required to perform an exercise test properly. A physician and other medical personnel and the standard pediatric resuscitative equipment must be immediately available to the laboratory in the event of an emergency. These recommendations are intended for diagnostic exercise testing. Maximal exercise testing of normal pediatric age volunteers for research purposes can safely be done by individuals with American College of Sports Medicine certification (or with equivalent training in pediatric exercise testing) without direct physician supervision of the test procedure.

Consent

The laboratory’s personnel should respect the right of the subject, parent, or guardian to be informed about the test and the associated risks. A meaningful written consent for the procedure is obtained by most laboratories. The subject should always be allowed to terminate the test upon request.

Patient Population

Each patient should be given a general explanation of the laboratory equipment and the test procedure. The patient should be instructed to avoid food intake for at least 2 hours before the study and to wear comfortable clothing and shoes, preferably flexible sports shoes. A history that includes a review of medications, a physical examination, and a resting supine 12-lead electrocardiogram provide information that will identify individuals for whom the test is either contraindicated or should be performed only with special considerations. A cardiologist may be consulted before testing if the patient’s symptoms suggest a cardiovascular disorder.

Relative Contraindications and Special Considerations

Previous publications concerning pediatric exercise testing have included contraindications, relative contraindications, and special considerations that were extrapolated from standards and guidelines for adult exercise testing.24 As with any stress-inducing procedure, the need for the information to be obtained by exercise testing must be carefully weighed against its risks. However, even for children whose diagnoses place them in a high-risk group there may be compelling reasons to perform exercise testing. For example, young patients, even those for whom limitations have been recommended on competitive activity, may be more physically active when unsupervised than their cardiologist or parents are aware. A carefully observed laboratory exercise test performed under controlled circumstances can be safer than the unsupervised activity of high physical intensity on the playground. Although serious cardiac decompensation with exercise testing can occur in adults, it is extremely rare in children.

Appropriate monitoring, equipment for the management of complications of testing, training of laboratory
personnel in pediatric basic and advanced life support, staff experience in test performance and interpretation, and the availability of medical staff backup are all required for the safe diagnostic testing of children referred to a hospital laboratory. A physician’s presence during all pediatric exercise tests, however, is not routine. For these guidelines, we have provided examples of situations in which the physician’s availability but not actual presence is required. Such situations may include:

1. The assessment of physical working capacity in healthy children for research purposes
2. Evaluation of chest pain that is not thought to be anginal in origin
3. Follow-up of postoperative patients assessed to have good hemodynamics after repair with testing to evaluate physical working capacity, to screen for arrhythmias, or as a baseline for cardiac rehabilitation programs
4. Evaluation of premature atrial or ventricular contractions in an otherwise healthy child (only if the QT interval is normal)
5. Routine follow-up of children with known arrhythmias or with permanently implanted artificial pacemakers
6. Follow-up of patients with previous Kawasaki disease or with other known coronary abnormalities as a screening for ischemic electrocardiographic changes with exercise (excluding those with giant coronary aneurysms or known ischemia)
7. Testing of asymptomatic patients who have been assessed as having mild to moderate aortic stenosis by clinical or echocardiographic criteria
8. Evaluation of physical working capacity in asymptomatic or minimally symptomatic cases with other congenital or acquired cardiac malformations.

Other situations may occur in which testing by the exercise laboratory personnel may be appropriate after review by the physician. Criteria for such situations should be established for each laboratory based on the capabilities of the technical personnel and the characteristics of the referral population. The procedure to order testing in the laboratory should permit the referring physician to request physician supervision if there is reason for special concern.

However, pediatric exercise testing is by no means risk free. In some situations the risk of maximal exercise testing is of such great magnitude that the significance of the information to be obtained from the test cannot outweigh the threat to the child’s care. Examples of diagnoses for which the risk of exercise testing is likely to result in a decision to defer or cancel testing include:

1. Severe pulmonary vascular disease
2. Poorly compensated congestive heart failure
3. Recent myocardial infarction
4. Active rheumatic fever with carditis
5. Acute myocarditis or pericarditis
6. Severe aortic stenosis
7. Severe mitral stenosis
8. Unstable arrhythmia, especially with compromised hemodynamics
9. Marfan syndrome with suspected aortic dissection
10. Uncontrolled, severe hypertension
11. Evidence of hypertrophic cardiomyopathy with a history of syncope

### Indications to Terminate an Exercise Test

There are three general indications to terminate an exercise test: when diagnostic findings have been established or a predetermined end point has been reached, when monitoring equipment fails, or when signs or symptoms indicate a potential hazard to the patient that may result in injury. Warning symptoms include pain, headache, dizziness, syncope, excessive dyspnea, or fatigue. Signs indicating test termination include ST segment depression or elevation greater than 3 mm; significant arrhythmia precipitated or aggravated by the exercise testing, such as premature ventricular contractions with increasing frequency, supraventricular tachycardia, ventricular tachycardia, or atrioventricular conduction block; or a progressive decrease in blood pressure.

### Exercise Studies in Specific Disease States

Exercise studies provide useful clinical information for monitoring response to therapy and about fitness, the potential for inducing arrhythmias, cardiac ischemia, and blood pressure response. Diseases for which studies may be useful include congenital heart disease, acquired valvular heart disease, cardiomyopathy, chronic lung disease, Kawasaki disease, systemic or pulmonary hypertension, and sickle cell disease. Exercise studies can be individualized by varying protocols to answer specific diagnostic questions. Table 6 outlines some findings from exercise studies in several specific cardiac diseases and provides information on expected responses, pathological responses, and clinical use.

### Protocols

Because performance on exercise tests largely depends on the type of exercise and the testing protocol, exercise testing should be performed in a standardized and systematic manner. Standardized protocols make collaborative research efforts possible as well as permit the reliable comparison of results of repeated testing of the same individual, of individual test findings with established norms, and of tests performed in different laboratories.

Most protocols in wide use involve a progressive increase in rates of work without a resting period between changes of work rate increments. Intermittent or discontinuous graded protocols involve a rest period between each change in rate of work. Although cumbersome for routine diagnostic testing, these discontinuous protocols have value in research projects in which comparatively long durations at steady state are required for data accumulation. Several protocols using the cycle ergometer or treadmill have been used in children. Pediatric exercise testing laboratories must accommodate subjects of various sizes and ages. The best exercise testing protocol for children depends on the information required and the age, health, and fitness level of the subject. The familiarity of the laboratory staff with specific treadmill and cycle protocols must be considered. The protocols described here are widely used in pediatric cardiac centers. Because of subtle variations in testing procedures, it is optimal to use normal data generated in one’s own laboratory rather than to rely solely on published normative data.
<table>
<thead>
<tr>
<th>Lesion</th>
<th>Common Findings</th>
<th>Findings That Warrant More Concern</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aortic stenosis</td>
<td>None</td>
<td>Ischemic ST changes</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Decreased BP response</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Exertional symptoms</td>
</tr>
<tr>
<td>Postoperative aortic stenosis</td>
<td>ST changes may be seen</td>
<td>Arrhythmia</td>
</tr>
<tr>
<td></td>
<td>without predicting residual gradient</td>
<td>Low VO\textsubscript{2}</td>
</tr>
<tr>
<td>Aortic insufficiency</td>
<td>Same as postoperative AS</td>
<td>Decreased BP response</td>
</tr>
<tr>
<td>Pulmonary stenosis</td>
<td>None expected</td>
<td>Same as postoperative AS</td>
</tr>
<tr>
<td>Postoperative pulmonary stenosis</td>
<td>None expected</td>
<td>Rare with very severe PS</td>
</tr>
<tr>
<td>Aortic coarctation, preoperative or postoperative</td>
<td>Hypertension</td>
<td>None expected</td>
</tr>
<tr>
<td></td>
<td>Arm-to-leg BP gradient</td>
<td>Ischemia</td>
</tr>
<tr>
<td>Atrophic septal defect</td>
<td>Normal</td>
<td>Low working capacity</td>
</tr>
<tr>
<td>Ventricular septal defect</td>
<td>None expected</td>
<td>Low working capacity if large shunt</td>
</tr>
<tr>
<td>Mitral regurgitation</td>
<td>None expected</td>
<td>Low working capacity</td>
</tr>
<tr>
<td>Mitral prolapse</td>
<td>False-positive ST changes common; ST changes with hyperventilation</td>
<td>Arrhythmia</td>
</tr>
<tr>
<td>Hypertension</td>
<td>Normal rise in BP with exertion; BP levels above normal for rate of work</td>
<td>Ischemia</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Arrhythmia</td>
</tr>
<tr>
<td>Cyanotic heart disease, palliated</td>
<td>Low chronotropic response</td>
<td>Low working capacity</td>
</tr>
<tr>
<td></td>
<td>Desaturation with exercise</td>
<td>Neuropathologic changes</td>
</tr>
<tr>
<td>Postoperative tetralogy of Fallot</td>
<td>Decreased chronotropic response</td>
<td>Low physical capacity</td>
</tr>
<tr>
<td></td>
<td>Right bundle branch block</td>
<td>Drop in BP</td>
</tr>
<tr>
<td>Postoperative arterial switch procedure</td>
<td>Uncertain significance of suggestions of ischemia</td>
<td>Limited long-term data</td>
</tr>
<tr>
<td>Postoperative Mustard procedure</td>
<td>Decreased chronotropic response</td>
<td>Arrhythmia</td>
</tr>
<tr>
<td></td>
<td>Low physical capacity</td>
<td>Desaturation</td>
</tr>
<tr>
<td></td>
<td>ST changes in right precordial leads</td>
<td>Profound cyanosis</td>
</tr>
<tr>
<td>Postoperative Fontan</td>
<td>Low physical working capacity</td>
<td>Arrhythmia</td>
</tr>
<tr>
<td></td>
<td>Desaturation</td>
<td>Abnormal wall motion</td>
</tr>
<tr>
<td></td>
<td>Drop in BP during exercise</td>
<td>Abnormal ST changes</td>
</tr>
<tr>
<td>Kawasaki disease</td>
<td>None expected</td>
<td>Perfusion abnormality (nuclear)</td>
</tr>
<tr>
<td>Cardiomyopathy</td>
<td>Low physical working capacity</td>
<td>Syncope, light-headedness</td>
</tr>
<tr>
<td></td>
<td>Low peak HR; low VO\textsubscript{2}</td>
<td>Ischemic ST changes</td>
</tr>
<tr>
<td>Postoperative cardiac transplant</td>
<td>Slow rise in heart rate</td>
<td>Ischemic ST changes</td>
</tr>
<tr>
<td></td>
<td>Normal working capacity</td>
<td>Low working capacity</td>
</tr>
<tr>
<td></td>
<td>Slightly low peak HR; normal VO\textsubscript{2}</td>
<td>Abnormal (over or under) sensing</td>
</tr>
<tr>
<td>Cardiac pacemakers</td>
<td>Wenkebach at upper rate limit</td>
<td>Ventricular arrhythmias</td>
</tr>
</tbody>
</table>

BP indicates blood pressure; AS, aortic stenosis; PS, pulmonary stenosis; and HR, heart rate.
Treadmill Protocols

On the treadmill, rate of work is advanced by increases in either slope, usually expressed as a percent, belt speed, or both. Percent slope indicates the number of feet in elevation for each 100 feet of distance traveled.

Bruce Protocol

Cumming et al.\textsuperscript{10} have provided physiological data and endurance time norms for the Bruce protocol when used for children between 4 and 14 years of age. This continuous graded protocol uses stages at which the speed and grade are progressively increased at 3-minute intervals from 1.7 through 6 mph and from 10\% through 22\%, respectively. The goal is to reach the level of maximal voluntary effort at which the subject is unable to continue.

The advantages of this protocol are that it may be used for all ages. Physiological responses to submaximal workloads can be measured, and longitudinal data can be obtained in a given subject by using the same protocol as he or she grows.

The potential disadvantages include that the test is longer than some other protocols, and younger subjects may become bored. This protocol may be inconvenient for testing highly fit individuals because subjects must wait until 12 minutes into the test before beginning a slow run (and then at an 18\% slope).

Balke Protocol

This type of treadmill protocol incorporates a constant treadmill speed with increasing slope. Riopel et al.\textsuperscript{11} report normal heart rate and blood pressure data in healthy children tested with a modified Balke protocol, which progressively increases the grade from 2\% to more than 10\% at 2\% increments until exhaustion while maintaining a constant speed of 3.5 mph. This continuous protocol is well suited for the unfit, the obese, the very young child, or the chronically ill individual.

A potential disadvantage is that active, fit, young subjects may find the test duration too long and the slope too shallow. The test may be modified and shortened by beginning the protocol at a high initial grade (between 6\% and 10\%). The speed can be adjusted to fit the subject's age and fitness level as another means of controlling the test time. When a laboratory changes the standard protocol, it is imperative that normative data be obtained on healthy matched controls.

Cycle Protocols

Most of the various cycle protocols call for a cadence rate of between 50 and 60 rpm, different stage lengths (between 1 and 3 minutes), and methods for adjusting the initial and incremental work loads.

James Protocol

Specific exercise protocols are based on body surface area. When three progressive stages (each stage is 3 minutes long) have been successfully completed, work load is increased by either 100 or 200 kg-M/min until a maximal level of voluntary effort is reached, and then the test is terminated. The goals of this protocol are to reach a state of exhaustion or predetermined end point, to estimate the highest rate of work (maximal power output), and to measure other physiological variables. Normative data have been provided by James et al.\textsuperscript{16} and Washington et al.\textsuperscript{28}

Godfrey Protocol

This continuous protocol consists of a specific exercise program for each of three height groups. Work loads are increased at intervals of 1 minute until a level of exhaustion is reached. The maximal power output or highest rate of work achieved is measured and compared with normal values for size and gender. Godfrey has published normative pediatric data obtained by using this protocol.\textsuperscript{22}

Strong Protocol

Exercise programs are designed for each of four groups according to body weight. The work load within each program is estimated to produce a heart rate at or near the expected value after successful completion of levels 1 through 3. Subsequent work loads are increased at increments of 75 to 300 kg-M/min at 1-minute intervals according to the size and current performance of the subject. The goal of this protocol is to determine physical working capacity at a heart rate of 170 beats per minute and to determine the highest rate of work producing exhaustion or predetermined end points. Normative data have been provided by Alpert et al.\textsuperscript{17,25}

Summary

Exercise testing of children differs from adult exercise testing in many ways beyond the technical issues related to test performance that are addressed in this report. Disease processes that produce myocardial ischemia are relatively rare in children compared with adults. Exercise testing may be useful in these cases, but the use of testing to assess functional capacity or cardiac rhythms will be encountered more often. Although the precise role of exercise testing in patient evaluation or long-term management of the cardiac patient will vary somewhat from center to center, exercise testing is often essential to diagnose and to direct treatment in a wide variety of clinical problems. An understanding of the role of exercise testing for children with known or suspected heart abnormalities is an essential part of the training of pediatric cardiologists. The staff of the pediatric exercise laboratory should be available to discuss with the clinician when a test might be of value in a specific case in addition to providing advice about the specifics of the performance of the test and offering age- and size-appropriate normal data from the laboratory with test interpretation.
In order to evaluate the functional performance and capacity of the heart, lungs, and blood vessels, I hereby consent voluntarily to the performance of an exercise test on my child, __________________________. I understand that the patient must walk or run on a treadmill, or pedal a bicycle until the limits of fatigue, breathlessness, chest pain, and/or other symptoms are of such severity that the test should be stopped. The electrocardiogram will be continuously monitored and blood pressure will be taken intermittently during exercise and for a prescribed time following exercise. Occasionally other indicated measurements will be performed. A physician will be present or in the immediate area.

I understand that the potential risks of testing include changes in the rhythm of the heart and the possibility of excessive changes in blood pressure. Thus, there is a remote chance of fainting and an unlikely chance of a heart attack. I understand that professional supervision by an Exercise Physiologist or physician will protect my child against injury, by providing appropriate precautionary measures. In the event that the precautionary measures are insufficient, hospital treatment will be available for my child.

I understand that the benefits of testing include quantitative assessment of working capacity and critical appraisal of the disorders or diseases that impair capacity, and that this knowledge facilitates better treatment and more accurate prognosis for further cardiac events.

I have been assured that I have the right to withdraw my child from the test at any time, that confidential information about the test result will not be given to non-medical persons without my consent, and that the welfare of my child will be protected.

The procedures and risks of the graded exercise test have been explained to me and I have read this form and have had an opportunity to ask any questions pertaining to the test. I understand the test procedures that will be performed and give my consent voluntarily.

Date: ___________________________  ___________________________  ___________________________

Parent or Guardian
Witness

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