EXERCISE TESTS IN CHILDREN

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SUMMARY

In this review, the basic principles of exercise physiology and their application in exercise tests are discussed. These tests include the six-minute walk test, step test, cycle ergometry and treadmill. While some of these tests are simple, inexpensive and do not require specific instruments, they provide important data for clinical use, e.g. exercise tolerance in children with chronic lung disorders such as cystic fibrosis; others, e.g. measurement of VO_2max, require elaborate and expensive equipment. General practitioners and community paediatricians should have a working knowledge of these simple exercise tests and their value. The more elaborate exercise tests should be fully made use of in the precise assessment of the cardio-respiratory and metabolic responses to exercise, exercise intolerance caused by certain diseases, e.g. interstitial pulmonary fibrosis and paediatric chronic obstructive airway diseases. These parameters would be important to monitor the clinical progress and should allow more optimal timing of interventions.

INTRODUCTION

For all young animals, life is a series of activities or exercises that range from rest and grooming oneself to strenuous playing with others in the group. A child's quality of life is therefore related closely to the child's ability to perform various exercises. For the paediatrician, precise assessment of the cardio-respiratory and metabolic responses to exercise provide an understanding of the mechanisms of exercise intolerance and assessment of its impact.[1] Methodologies and standardised approaches to exercise testing are in a current state of flux as new techniques are developed and new information is gained from them. This review aims at providing basic information about exercise tests in general and their use in children in particular.

BASIC PHYSIOLOGY OF EXERCISE

Exercise requires muscle contraction which is made possible by the availability of adenosine triphosphate (ATP). Adenosine triphosphate production is derived from the aerobic and anaerobic metabolism of glucose, sometimes fat and rarely protein. Aerobic metabolism, which consumes oxygen, is preferred because ATP is produced more efficiently under aerobic conditions. This oxygen consumption, VO_2, is matched to oxygen delivery, DO_2. DO_2 is a product of cardiac output and arterial/mixed venous oxygen content difference, i.e. $DO_2 = Q \times Hb \times (SaO_2\text{-}SvO_2) \times 1{\cdot}34$. At rest, oxygen consumption is around 3–5 ml/kg/min. This rises to 30 ml/kg/min in healthy athletic children after strenuous exercise. Anaerobic threshold refers to the highest level of exercise that can occur without inducing sustained increase in lactic acidosis.

LEVEL OF EXERCISE (OR WORK CAPACITY)

The level of exercise can be divided into five grades (Table 1), from very light to very heavy exercise.[2] During moderate exercise, the energy demand is below the subject's anaerobic threshold and the arterial blood lactate is not raised. During heavy exercise, the energy demand is above this anaerobic threshold, resulting in the arterial lactate becoming elevated but remaining constant. During very heavy exercise, the energy is well above the anaerobic threshold and the blood lactate continues to rise in step. As this is an unsteady state, the level of work cannot be sustained.

TABLE 1
Level of exercise

Level	$\%VO_2$max	%HRmax
Very light	<30	<35
Light	30–49	35–59
Moderate	50–74	60–79
Heavy	75–84	80–89
Very heavy	>85	>89

MEASUREMENT OF EXERCISE CAPACITY

Exercise capacity is expressed as one of the following indices: (1) oxygen consumption, (2) watts, (3) kilopond meters per minute (kpm) (kp refers to the force acting on the mass of 1 kg at the normal acceleration of gravity). Oxygen consumption serves as a physiological index of the rate of energy expenditure. The relationship between these indices of exercise capacity is summarized (Table 2).[3]

MEASUREMENT OF OXYGEN CONSUMPTION

In adults, the oxygen consumption at rest is around 200–250 ml per minute. Oxygen consumption increases by approximately 12 ml per minute per watt. Maximal oxygen uptake (VO_2max) refers to the level of oxygen consumption of a subject beyond which higher workload does not result in increased oxygen consumption. Instead, the additional workload is met by energy produced from anaerobic metabolism. The cardiac output is the limiting factor for VO_2max in normal subjects. Most of the increase in cardiac output derives from an increase in heart rate. The cardiac output is approximately five litres plus the VO_2 times five, i.e. Q = 5 L + VO_2 x 5. A healthy young 70-kg adult should be able to maintain a VO_2max of about 3L/min. A sedentary existence without exercise can reduce VO_2max to half of the expected value. VO_2max is thus commonly used in exercise physiology as a measurement of cardio-respiratory fitness. The VO_2max is achieved by a combination of increase in cardiac output (up to five times), increased oxygen extraction by tissue (up to three times), and minute ventilation, i.e. the volume of air breathed out per minute, (up to eight times).

Table 2
Relationship between 0_2 consumption and other measures of work.

O_2 consumption (ml/min)	Kpm/min	Watts	METS*
225	0	0	1
900	300	50	4
1,500	600	100	7
2,100	900	150	10
2,800	1,200	200	13
3,500	1,500	250	16
4,200	1,800	300	19
5,000	2,100	350	22

* Metabolic Equivalents

During heavy exercise, the total work exceeds the capacity of aerobic work. The deficit is made up by anaerobic metabolism, of which the principal product is lactic acid. Lactic acid begins to cause distress at levels above 11 mmol/L, which is ten times the normal resting level. Lactate accumulation seems to be the limiting factor for sustained heavy work whilst in moderate to severe exercise, the limiting factor of exercise is the degree of shortness of breath (SOB) or dyspnoea.[4] Shortness of breath is a subjective feeling of 'high' proportion of the maximal breathing capacity (MBC), with this defined as the maximal minute volume of ventilation that the subject can maintain for 15 seconds. MBC is obtained by asking the subject to breathe in and out of a spirometer without the need for removal of carbon dioxide. Dyspnoea ensues when ventilation reaches about a third of MBC. In normal subjects, 60% of MBC can usually be maintained with difficulty for 15 minutes.

In children with moderate to severe lung diseases, the VO_2max is limited by their decreased MBC. In addition to their reduced ventilatory reserves, patients with lung diseases have increased ventilatory requirements for a given level of exercise because of increased physiological dead space. Moreover, the physiological dead space does not decrease with exercise in those with lung diseases, in contrast to healthy individuals.

AGE-RELATED EXERCISE CAPACITY

In proportion to their size, younger children are able to produce less power than older subjects. (VO_2max increases in roughly direct proportion to body weight.) Compared with adults, children have a faster recovery of heart rate and ventilation after high intensity exercise. This difference in recovery is not well understood, but it may be related to the difference in the rate of production of lactate, hydrogen ion and catecholamines during exercise.

PHYSICAL FITNESS

Physical fitness includes several components: 1) body composition (i.e. lean and fat body mass); 2) muscular fitness like muscle strength, endurance and flexibility; and 3) cardiorespiratory endurance. Body composition is assessed by skin fold measurement, body mass index, and dual energy X-ray densitometry. VO_2max traditionally indicates cardio-respiratory endurance. The word 'fitness' is often used broadly as a global indicator of the exercise response when fitness tests are actually designed to assess task-specific capability of the cardiorespiratory system or the musculo-skeletal system. Hence, medical practitioners should avoid the vague term 'physical fitness' for a specific patient, and instead should compare the data obtained from specific tests with previous data for the same tests and norm reference values. It is also important to realise that one's specific area of fitness as assessed by certain instruments, e.g. cycle ergometer, depends partly on one's familiarity with this instrument. This has some importance in testing children as one must ensure that the child being tested is comfortable with the chosen instrument, which is usually either a cycle ergometer or a treadmill.

INDICATIONS FOR EXERCISE TESTS IN CHILDREN

The three indications to study individuals while they perform exercise.are: 1) an exercise test that can quantify the degree of cardiorespiratory endurance by assessment of an individual's oxygen consumption during maximal exercise (VO_2max). Comparison of VO_2max with an age and sex-matched controlled population is informative for assessing an individual's cardio-respiratory endurance and serves to monitor the disease progress. 2) Excercise testing can help to elucidate the etiologies for the observed exercise intolerance. Analysis of the results of the exercise tests helps to indicate whether the limiting factor is a pulmonary problem, a cardiac problem, a lack of conditioning of muscles or poor volition. Meanwhile, it also serves to monitor the progress of the disease. 3) Responses to various treatments (e.g. inhaled steroids in asthma) can be assessed.

CHOICE OF EXERCISE TESTS5

Exercise tests can be classified by complexity. Simple tests require little or no equipment and include a time standardized walk, e.g. a six-minute walk, the three-minute step test, or the grip test for muscle strength. Moderately complex tests entail the use of some equipment, and include the measurement of FEV-1 and FVC, plotting of flow/volume loop and measurement of oxygen consumption and heart rate. More complex tests involve the measurement of oxygen consumption, carbon dioxide production, cardiac output and other measurements derived from them.

Subject to availability, choice of the appropriate test for children depends on the specific clinical questions being asked and the aspect of exercise tolerance that is of interest. For example:

Is the exercise intolerance related to airway hyperresponsiveness?

Then measurement of FEV-1 before and after six minutes of exercise would be appropriate.

Are ventilatory and cardiac responses to progressively increasing workloads appropriate?

Traditional progressive cycle or treadmill test together with measurement of VO_2 max and cardiac output would be required.

How much oxygen is needed to prevent exercise desaturation?

A simple double test on treadmill or cycle will give the answer: one that is carried out in room air at progressively more difficult loads until desaturation occurs, and then another with supplemental oxygen at that workload. If desaturation still occurs, the tests will be repeated with a higher FiO_2.

What is the ability of the patient to perform work during real-life situations and the cost of that work in terms of oxygenation and heart rate?

A two, six or 12-minute walk test or three-minute step test can provide that information (in specific terms of distance walked in the given time). This can serve as a baseline for comparison with results after intervention and act as a monitor of disease progress.

What is the muscle strength?

A strength measure, e.g. the maximum amount of weight liftable at one time, would be appropriate.

DETAILS OF DIFFERENT EXERCISE TESTS: EXERCISE-INDUCED AIRWAY HYPER-RESPONSIVENESS

Exercise-induced asthma (EIA) occurs in about 60–80% of asthmatic children.[6] When normal healthy children exercise, lung function changes little or may even improve. Towards the end of exercise or a few minutes later, lung function begins to fall, with the maximum fall occuring five to ten minutes after the end of exercise. Recovery in lung function takes place in about 30 to 45 minutes. The upper limit of post-exercise fall in FEV-1 in normal children was found to be 6–8%. Exercise-induced bronchial reactivity is found only in asthmatics whilst methacholine bronchial hyper-reactivity is found in asthmatics and paediatric chronic obstructive pulmonary diseases (including bronchiectasis, primary ciliary dyskinesia, bronchiolitis obliterans, cystic fibrosis).[7]

Indications of testing for exercise-induced hyper-responsiveness (EIA):

1. assessment of severity of bronchial obstruction after exercise;
2. evaluation of efficacy of a specific therapy to prevent EIA;
3. differentiation of asthma from other chronic obstructive lung diseases during childhood.

METHODOLOGY

Children should avoid physical activities for at least three hours before exercise testing or they may show an attenuated response due to refractoriness, thought to be related to the release of prostaglandins during exercise. Medications that can influence the pulmonary response to exercise should be stopped prior to the test: six and 12 hours for short and long-acting beta-adrenergic drugs, respectively; eight hours for anti-cholinergic drugs; and 24 hours for the cromolyn group of drugs. Corticosteroids can be continued. Baseline pulmonary function (FEV-1) should be at least 65% of the predicted value, and either a cycle ergometer or a treadmill can be used. One standard test is a six-minute run on a treadmill at a speed of three to five mph with a slope of 10%.[8] This will result in an oxygen consumption of about 60 to 80% of VO_2 max and a heart rate of 170 to 180 bpm. Lung function is measured before exercise and is repeated until satisfactory reproducibility is demonstrated. Measurements are performed in duplicate (recording the best value) at one, three, five, ten and fifteen minutes after exercise. A 10% or greater fall in FEV-1 or PEF is considered a positive response for exercise-induced intolerance. Inhaled beta-adrenergic medications, e.g. salbutamol or terbutaline, should be available in the test laboratory to relieve any symptomatic drop in FEV-1 or PEF.

EXERCISE TESTS OF 'REAL-LIFE' WORK

The 12-minute walk documenting the distance covered is commonly used in adults.[9] In children, walk tests of two, six and 12-minute duration were validated as useful tests in cystic fibrosis patients and were found to be useful in an intervention study.[12] Another test is the three-minute step test. Outcome measures include distance covered, lowest SpO_2 reading, highest heart rate reading and the degree of breathlessness (a subjective visual analog score or an objective 15-count breathlessness score).[10]

The methods of performing the six-minute walk test and the step test are elaborated here. The six-minute walk test is performed on level ground, usually along a corridor marked at two-meter intervals. Patients are instructed to try to cover as much distance as possible in six minutes at their own pace, being assured that they can rest at any time during the test. A wheelchair was pushed behind the patient for any necessary rest stops. Patients are informed of the time at 30-second interval, but are given no verbal encouragement. Optimally, children should be allowed to practise the walk until they are used to it. During the test, a pulse oximeter is used to monitor heart rate and SpO_2. The patient's arm is placed in a sling to hold the hand and finger probe in a horizontal position and to provide stable measurements, and these are recorded at 30-second intervals. Walk distance, peak heart rate and lowest SpO_2 are recorded. The walk distance is directly correlated with VO_2max.[10, 11] For children with chronic lung diseases, e.g. cystic fibrosis, the walk distance was significantly related to FEV-1.[11] The lowest SpO_2 recorded during the six-minute walk test is found to be significantly related to that obtained from progressive exercise test using a cycle ergometer. However, the peak heart rate obtained with the six-minute walk test is significantly lower than that obtained from the progressive exercise test using a cycle ergometer.[11] Hence, different challenges produce similar response in one parameter, i.e. SpO_2 and a different response in another parameter, peak heart rate. These heterogeneous responses are common in exercise tests.[12]

The three-minute step test is performed with the child stepping up and down a single step at a height of 15 cm.[13] The work performed in test is a product of the stepping height, the rate, the weight and height (particularly the leg length). The step rate, 30 per minute, is controlled by a metronome. The outcome parameters include lowest SpO_2 reading, highest heart rate and change of the modified Borg dyspnoea score.[14] Patients can stop if they feel tired or if the SpO_2 fall below 75%, in which case the total number of steps taken is calculated. Patients are given standard encouragement and shown how to change the leading leg to reduce localized muscle fatigue. This test is more convenient for monitoring than the walk test as the child is moving on the same spot. This test is also less dependent on the patient's motivation as the rate is controlled. Disadvantages of the three-minute step test include its lack of resemblance to daily activity and its workload being dependent on the height and weight of a subject.

VENTILATORY AND CARDIAC RESPONSES TO PROGRESSIVELY INCREASING WORKLOADS

The two commonest testing devices are the cycle ergometer and the treadmill. Usually the treadmill is the instrument of choice because the exercise is more familiar to the subject. In treadmill exercise, oxygen consumption is dependent on the subject's weight, and also the speed and incline of the treadmill. A nomogram is available for easy reference.[15] It must be borne in mind that the oxygen uptake is reduced in subjects who are familiar with the procedure. Hence, a subject should be allowed to practise on the treadmill before the formal test so as to improve the validity of the test as an assessment tool. The modern treadmill is a continuous belt which is moved across a smooth platform by an electric motor; the platform is provided with handrails. The mouthpiece supported on a gantry which is linked to the incline of the platform. The speed of the belt and the angle of incline are adjustable, the former usually over the range 0–14·5 kph (0–9 mph), the latter from horizontal to an incline of one in six (17%). The subject should stand on the platform and face the appropriate direction with the belt stationary. As a safety measure, a chain is hooked across the platform behind the subject at the height of the buttocks or a safety harness is worn. The operator steps up the speed from zero gradually until the desired speed is reached. The subject is instructed to stand erect with head up, and to take long steps and lift the feet only to the extent which is required for normal walking. The handrail can be held at the start of exercise but the rail should be released before measurement is begun. As an additional precaution, there should be a safety button within the reach of the subject for decelerating the belt. An abrupt end to the forward motion is undesirable as this can lead to the subject being propelled forward by his kinetic energy.

In cycle ergometry, the work rate input is determined by the load on the cycle's flywheel and the subject pedals at a constant rate. Most cycle ergometers are calibrated in watts or in kpm per minute, and the oxygen consumption can be obtained as from Table 2. Consequently, the fundamental difference between these two input devices is that with the cycle ergometer, the work rate (power) input is known precisely, while with treadmill exercise the external work rate can only be estimated from body weight, slope and velocity of the treadmill. VO_2max during cycling is on average 10% lower than that obtained from treadmill, except in experienced cyclists.[16] Another benefit of the cycle ergometer is the change in exercise level is achieved by altering the load on the flywheel, which is much less obvious than the change in the incline or speed as required for treadmill. Obvious changes often evoke anxiety and may result in a change in the muscle groups involved in the exercise. The disadvantage with cycle ergometers is that the child may not be adept at bicycle riding; the investigator must therefore always be aware that cardiorespiratory responses are task-specific. Hence, one may underestimate the fitness of a child who is good at, for example, swimming but who has never ridden a bicycle. A second disadvantage is that the child is required to maintain a constant pedaling rate, particularly at low work rates. This can be compensated for by specially designed ergometers in which the external load is adjusted to the pedaling rate to maintain a constant work rate. Cycle ergometry with handgrips instead of pedals is used to study the responses to exercise with the arms.

The child undergoing exercise test should be placed in an environment with little distraction. A child also requires gentle, continuous verbal encouragement during the test. Gas exchange analysis systems are of two general types: continuous-measurement (breath-by-breath) and discrete measurement (requiring mixing chambers of the exhaled gas). Both systems can yield useful and accurate information on cardiorespiratory responses to exercise. The usual progressive exercise protocol lasts between ten and 15 minutes, and usually the test is performed at work rates that are above the subject's lactate or anaerobic threshold during the second half of the test. It must be realized that maximal exercise tests are not representative of patterns of physical activities actually encountered in children. It was shown that children normally engaged in low and medium intensity activities 77% of time and high-intensity activity 3·1% of the time from 8 a.m. to 8 p.m.[17] Normal reference range values of maximal exercise tests are obtained from studies carried out in large samples of healthy children. These values are profoundly effort-dependent, and healthy subjects are routinely cajoled and prodded to continue exercising in the high-intensity range to achieve data of optimal quality. In contrast, patients with known or even suspected abnormalities are not encouraged as vigorously as are healthy subjects. Lactic acidosis, and respiratory or cardiac insufficiency can accompany high work rates, and this causes reasonable concern regarding the safety of high-intensity exercise testing in individuals with heart or lung disease. Hence, it is important to have qualified medical staff with appropriate equipment for emergency treatment by the side of the patient. His/her main tasks would be to stop the test if the child is clinically unstable and to respond to any complications, e.g. asthmatic attacks, arrhythmia. Consequently, published 'normal' maximal values may not be reliable for children with suspected impairment, for whom a progressive submaximal test is more appropriate.

SAFETY OF EXERCISE TESTING IN CHILDREN

The complication rate was 1·79% in one series of 1,730 studies.[18] It included chest pain, dizziness or syncope, and decreased blood pressure. Hazardous arrhythmias occurred in only 0·46% of subjects. No mortality was recorded.

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