Personal Practice

Cardiopulmonary Exercise Testing in Children

CCW ***Yu,*** AM ***McManus,*** AM ***Li,*** RYT ***Sung,*** N ***Armstrong***

Abstract The cardiopulmonary exercise test (CPET) is a noninvasive assessment that provides valuable insight into the health and functioning of the pulmonary, cardiovascular and muscular systems. A number of key variables are obtainable from the CPET which reflect varying degrees of pathophysiology and can provide valuable information on the cardiopulmonary function of a child. The response of the child to the acute bout of exercise of the CPET is quite distinctive from that of adults. In this review we describe the CPET in children, its assessment and interpretation. Available data on Hong Kong children are presented wherever possible.

Key words Cardiopulmonary exercise test; Children and Adolescents; Chinese; Hong Kong

Review Text

Treadmill running tests without the measurement of gas exchange have been used in hospitals in Hong Kong for the evaluation of cardiac arrhythmias and functional capacity in children and adolescents for many years. During the test, abnormal cardiac function such as arrhythmia and ischaemia can manifest by clinical symptoms or electrocardiograpic findings. Other physiological parameters such as changes in heart rate and blood pressure during the exercise test can also provide useful information on the subject's cardiovascular health status.[1]

The treadmill running test with the additional measurement of gas exchange to study an individual's ability to take-up, transport and utilise oxygen during an acute bout of exercise is called the cardiopulmonary exercise test (CPET). The CPET offers the possibility of determining the pathophysiology of exercise limitations and the severity of functional impairment. It has also been routinely used to evaluate the effect of medical, surgical, or rehabilitative treatment on cardiopulmonary function in both adults and paediatric patients and has greatly enhanced our understanding of cardiopulmonary development in children.[2] As a general rule children would undergo a CPET for the evaluation of exercise performance and/or the evaluation of mechanisms that limit performance. A summary of the common indications and contraindications for performing a CPET are given in Table 1. Readers are encouraged to refer to the American Heart Association statement on clinical stress testing in the pediatric age group for a more detailed discussion of these.[3]

Very often the cardiopulmonary exercise test focuses solely on the determination of maximal oxygen uptake ($\dot{V}O_2$ max). Whilst valuable, focusing solely upon $\dot{V}O_2$ max fails to fully utilise a great deal of additional information

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Table 1 A summary of the indications and contraindications for exercise testing in children and adolescents

Indications for exercise testing	**Absolute contraindications for exercise testing**
Evaluation of:	• Acute myocarditis, pericarditis or endocarditis
• Symptoms and signs induced by exercise	• Acute rheumatic fever
• Abnormal responses to exercise in cardiac or non-cardiac disorders	• Acute myocardial infarction
• Medical or surgical interventions	• Active pneumonia
• Functional capacity for vocational, recreational and athletic recommendations	• Active hepatitis
	• Severe systemic hypertension
• Overall fitness levels	• Acute phase of Kawasaki disease
	• Acute orthopaedic injury
Discover:	
• The prognosis for a specific disorder	**Relative contraindications for exercise testing**
	• Severe left-ventricular outflow tract obstruction
Establish:	• Severe right-ventricular outflow tract obstruction
• Baseline data for follow-up or rehabilitation programmes	• Congestive heart failure
	• Ischaemic coronary artery disease
	• Advanced ventricular arrhythmias
	• Pulmonary vascular obstructive disease
	• Pacemakers with defibrillation capabilities
	• End-stage cystic fibrosis

Adapted from Stephens P, Paridon SM. Exercise testing in pediatrics. Pediatr Clin North Am 2004;51:1569-87.[4]

regarding the capacity of the pulmonary and cardiac systems to deliver oxygen to the working muscle at both submaximal and maximal intensities. These additional variables are arguably more useful for the determination of exercise limitation and utilising all available data allows both general (e.g., determining whether exercise capacity is reduced) and specific (e.g., is a reduced ventilatory capacity limiting exercise) questions to be addressed.[5,6]

Extensive research has shown that the child's responses to exercise are unique and quite unlike those of adults.[7] The purpose of this review is to provide an overview of cardiopulmonary exercise testing in children, with an emphasis on the pulmonary and cardiac responses routinely available during a CPET. Wherever possible, published values for Hong Kong children are considered.

CPET Equipment, Protocols and Test Termination

Equipment and protocols designed for adult testing are still used to test children without consideration of the comfort of the child or the quality of data obtained. A laboratory suitable for testing children and adolescents must have a fully adjustable cycle ergometer (i.e., seats, handle bars and pedal crank length) and/or a treadmill with adjustable or additional handrails.[8] Smaller leads and cuffs are necessary for any electrocardiogram or blood pressure measurement and the gas analysis system must accommodate the smaller dead space requirements of the child. A paediatric sized mouthpiece and noseclip or mask should be available. We have demonstrated recently that children perceive significantly less discomfort when wearing the mask compared to the mouthpiece and noseclip, which may be an important consideration for increasing compliance during testing.[9] It should be remembered that avoidance of leakage is paramount when using the mask. Often the masks available are not suitable for the smaller Asian nose and ways to reduce leakage and ensure data quality have to be considered.

Ergometers

The highest values of $\dot{V}O_2$ max (or peak $\dot{V}O_2$, see later discussion under *Test Termination*) are obtained when a large muscle mass is utilised. The two most commonly used modes for laboratory determination of peak $\dot{V}O_2$ are the cycle ergometer and the treadmill. Cycle ergometers although robust, relatively cheap and easily calibrated, require a large effort in relation to muscle strength during maximal exercise. It is thought that increased peripheral muscular pain and an inability to maintain the pedaling rhythm cause premature test termination. Blood flow through the quadriceps is constricted during cycle ergometer exercise, which may lower venous return and cardiac output and increase peripheral fatigue. This is supported by the lower maximum heart rate (HR_{max}) values and higher blood lactate concentrations reported during cycle ergometer testing.[10] Cycle ergometer testing is more applicable for those patients with neuromuscular diseases affecting ambulation, or with children who have difficulty adapting to treadmill belt motion.[8]

Walking and running is a natural form of locomotion for healthy ambulatory children and treadmill running protocols elicit the highest peak $\dot{V}O_2$ values. In the younger child there is a risk of falling during treadmill running and testing will likely necessitate adult support. One noteworthy consideration when using the treadmill for CPET is the holding of the handrails. Holding the handrails diminishes the rate of increase in heart rate and $\dot{V}O_2$ and prolongs test duration.[8,11] We encourage, subjects, except in special circumstances, not to grip the handrails during the exercise test.

Protocols

Protocol selection should be based on the objectives of the test and the child being subjected to the least possible discomfort. Peak $\dot{V}O_2$ has been shown to be resilient to protocol changes and for this reason a wide variety of test protocols have been employed.[12,13] Other parameters such as the ventilatory response, are however highly dependent on the protocol and adequate care needs to be taken to choose the appropriate test approach. If submaximal data are desired, stage length must be at least two, preferably three minutes in duration to allow a steady state to be achieved in children. The test should allow for increments of equal length and work and result in an increase in $\dot{V}O_2$ of no more than 4 $mL.kg^{-1}\,min^{-1}$. When using the treadmill, overly steep slopes are to be avoided in children because of augmented peripheral fatigue and an increased risk of falling. Table 2 provides a summary of the general guidelines for the design of CPET treadmill protocols.

In clinical testing, the most widely used protocol in children is the Bruce protocol. Table 3 provides details of the Bruce protocol, as well as the stage adjustments for the Modified Bruce protocol, which is recommended when using the Bruce protocol for testing the frail or very sedentary. The advantages of the Bruce protocol include the ability to record submaximal responses; starting at slow speeds allows ample time for treadmill habituation and the protocol can be used across ages allowing longitudinal data collection.[14] However, despite being the protocol of choice in many clinical laboratories, the Bruce protocol fails to satisfy many of the guidelines suggested for protocol development, employing large and unequal workload

Table 2 General guidelines for designing treadmill CPET protocols for children and adolescents

1.	Safety is paramount. Contraindications must be ruled out prior to testing (see Table 1). At least two adults should conduct the test and both the child and testers must know the signal for test termination
2.	Testing should only be undertaken at least 2 h after eating
3.	No vigorous exertion on the day of the test
4.	Appropriate clothing should be worn (e.g., t-shirt, shorts and running shoes)
5.	Children should be given the chance to habituate to the treadmill and laboratory environment
6.	A low intensity warm-up should be carried out before the test begins
7.	Test duration should be no more than 12 minutes. If a discontinuous test is used, standard rest periods (usually 1 minute) between stages are advised
8.	A discontinuous test is necessary if ancillary measures such as blood sampling are needed
9.	Stage length should be at least 3 minutes if blood lactate is being assessed and at least 2 minutes if a near steady-state $\dot{V}O_2$ is required
10.	Changes in speed and gradient should be age-appropriate and not excessive
11.	Objective end-points for test termination should include HR levelling off at about 200 $beats.min^{-1}$ and RER ≥ 1.00
12.	Subjective end-points for test termination include facial flushing, sweating, hypernoea, unsteady gait
13.	A warm-down consisting of slow walking is necessary following test termination

increments. Rowland[8] notes that often the reasons given for using the Bruce protocol include "The adult laboratory is using it", "It's convenient because it's in our automated testing equipment" and "It provides some uniformity across laboratories, and we're able to compare it with published normal values." (p. 22). It is interesting to note that although the Bruce protocol is probably the protocol of choice currently employed in clinical settings in Hong Kong, there are no published peak $\dot{V}O_2$ values derived using this protocol in healthy youngsters for comparison to paediatric patients. The protocols used for treadmill determination of peak $\dot{V}O_2$ in non-clinical settings in Hong Kong have been remarkably alike, using increments similar in length and speed and there is clear consistency in the values reported by age and sex. Details of these are provided in Table 4. Given that peak $\dot{V}O_2$ is resilient to protocol changes, one would not expect values to alter if children were tested using the Bruce protocol; however, it should be remembered that other parameters are influenced by the protocol, and protocol choice must therefore match the specific aim of the investigation. It is also worth considering that the Bruce protocol begins with a large elevation and it would be prudent to explore whether this creates undue peripheral fatigue, which limits the ability of the child to reach maximum.

Table 3 The Bruce protocol

Stage	Speed ($km.hr^{-1}$)	Elevation (% gradient)	Duration (min)
1	2.7	10	3
2	4.0	12	3
3	5.5	14	3
4	6.8	16	3
5	8.0	18	3
6	8.8	20	3
7	9.7	22	3

N.B. The Modified Bruce protocol adds two stages to the beginning of the Bruce protocol to make the onset of testing less strenuous. Stage 1 of the Modified Bruce begins at 2.7 $km.hr^{-1}$ and 0% gradient, whilst stage 2 is at 2.7 $km.hr^{-1}$ with a 5% gradient. Stage 3 corresponds with stage 1 of the Bruce protocol above.

Test Termination

Regardless of the protocol chosen, it is essential that test termination is based on the same criteria for every child. Commonly a symptom limited test utilising a list of clinical indications for stopping an exercise test will be used with paediatric patients. However, many children with various disorders are able to exercise to maximum without adverse symptoms. The criterion for maximal exertion has traditionally been a leveling-off or plateau in $\dot{V}O_2$ despite an increase in exercise intensity.[15] Notably, both the theoretical and the methodological bases of the $\dot{V}O_2$ plateau concept have been challenged.[16-19] Åstrand[20] was the first to document that only a minority of children and adolescents terminate a progressive exercise test to exhaustion with a leveling-off in $\dot{V}O_2$. Subsequent studies have confirmed that

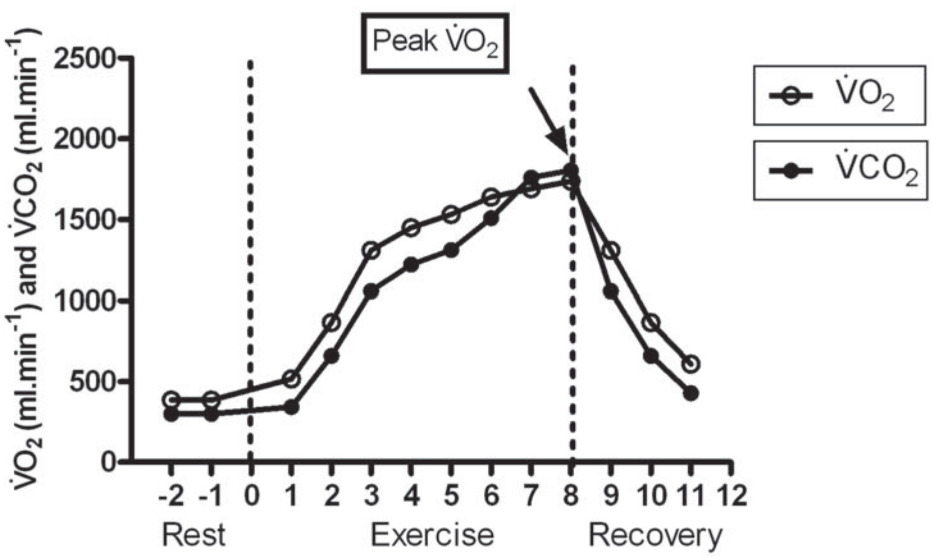

Figure 1 The responses of oxygen uptake and carbon-dioxide output during a CPET to maximum.

a $\dot{V}O_2$ plateau is not a prerequisite for the valid determination of young people's aerobic fitness[21,22] and it has therefore become widely recognised that the appropriate term to use with young people is peak oxygen uptake (peak $\dot{V}O_2$), the highest $\dot{V}O_2$ elicited during an exercise test to exhaustion.[23] Figure 1 provides an example of the $\dot{V}O_2$ and carbon dioxide output ($\dot{V}O_2$) response during a CPET to maximum. If a child or adolescent has been habituated to the laboratory environment and shows clear signs of intense effort supported by objective criteria (such as heart rate

Table 4 Laboratory Assessed Peak Oxygen Uptake in Hong Kong Chinese Children and Adolescents by age and sex

Ref.	Mode	Protocol	Age (years)		$\dot{V}O_2$ peak ($l.min^{-1}$)		$\dot{V}O_2$ peak ($ml.kg^{-1}min^{-1}$)	
			Boys (n)	Girls (n)	Boys	Girls	Boys	Girls
37	TM walk-run	Continuous, graded test. 3-minute stages at 5, 6, 8, 9 km/hr. Increases of 2.0% in gradient thereafter.	9.1±0.6 (n=18)	9.30±0.6 (n=44)	1.20±0.20	1.13±0.19	40.1±5.3	37.5±5.5
38	Cycle ergometer	Continuous incremental test,70 rpm, 4 minutes at 50 W, thereafter increases of 10 W every minute.	10.3±0.6 (n=35)	–	1.65±0.20	–	45.6±5.8	–
Data from ref. 39	TM walk-run	Continuous graded test. 2-minute stages at 5, 6, 8, 9 km/hr. Thereafter increases of 2.0% gradient every minute.	10.2±0.9 (n=111)	10.4±0.9 (n=109)	1.67±0.29	1.58±0.30	47.5±6.9	44.5±5.6
37	TM walk-run	Continuous, graded test. 3-minute stages at 5, 6, 8, 9 km/hr. Thereafter increases of 2.0% gradient every minute.	11.4±1.0 (n=8)	10.8±0.7 (n=8)	1.37±0.34	1.23±0.28	38.2±5.5	39.6±6.0
37	TM walk-run	Continuous, graded test. 3-minute stages at 5, 6, 8, 9 km/hr. Thereafter increases of 2.0% gradient every minute.	14.0±0.7 (n=14)	13.8±0.5 (n=26)	2.51±0.52	1.91±0.46	48.1±6.8	39.1±4.1
40	TM running	Discontinuous graded test. 3-minute stages at 8, 9, 10 km/hr. Increases of 2.5% in gradient thereafter.	13.7±0.4 (n=28)	13.6±0.3 (n=28)	2.66±0.44	1.96±0.35	50.3±6.4	40.4±3.3
41	TM running	Discontinuous graded test. 3-minute stages at 8, 9, 10 km/hr. Increases of 2.5% in gradient thereafter.	13.9±1.9 (n=28)	13.1±2.0 (n=21)	–	–	48.4±6.1	41.6±3.6
42	TM running	Continuous graded test. 2-minute stages at 8, 9, 10 km/hr. Increases of 3% in gradient thereafter.	14.8±1.4 (n=27)	14.5±1.6 (n=28)	–	–	53.9±5.6	45.1±4.6
43	TM running	Continuous graded test. 2-minute stages at 8, 9, 10 km/hr. Increases of 3% in gradient thereafter.	15.0±1.5 (n=86)	–	2.7±0.44	–	52.0±5.8	–

>95% of the predicted maximum and a respiratory exchange ratio=1.0) peak $\dot{V}O_2$ can be accepted as a maximal index of aerobic fitness.[22,23]

Data Processing

Gas analysis during the CPET is generally achieved using an automated gas analysis system, most of which allow breath-by-breath analysis. The reported $\dot{V}O_2$ represents the average for a chosen sample interval. Breath-by-breath systems allow per breath sampling (e.g., each breath, 8-breath averages) or per increment of time sampling (e.g., 10, 20 or 30 seconds). The sampling interval can have a major impact on gas exchange data, with overly large sampling (e.g., 30s) over-smoothing the data and artificially reducing the $\dot{V}O_2$ response.[19] During the determination of peak $\dot{V}O_2$ it is most common to use 20s or 8-breath sampling. Measurement of the oxygen uptake kinetic response requires a much denser data set and the necessity to use breath-by-breath output. The challenge with breath-by-breath data is addressing the large magnitude of noise (generated by the inter-breath variations of normal breathing) in the context of a relatively small $\dot{V}O_2$ response amplitude in children.[24] If this is not adequately addressed the interpretation of the oxygen uptake kinetic response lacks certainty and this is addressed later in the review (see sub-section Oxygen Uptake Kinetics). Rather than assume the manufacturer's default thought needs to be given to the choice of sample interval in the context of the required data. The chosen sampling method should always be reported to allow cross-study comparisons.

Information Available from a Cardiopulmonary Exercise Test

During a maximal cardiopulmonary exercise test the child's ability to deliver and utilise oxygen is placed under maximal stress until the ability to sustain further increases in exercise intensity becomes untenable. Systematic research over the past 50 to 70 years has shown key differences in the cardiopulmonary responses of children and adults to graded exercise, highlighting the need for child specific interpretation of CPET information.[7,25]

Pulmonary Function

Ventilation at peak exercise is a less-defined variable, perhaps because of its dependence on the protocol. During progressive exercise minute ventilation ($\dot{V}_E$) reflects increases in $\dot{V}O_2$ and $\dot{V}CO_2$. As exercise approaches maximum, the rise in blood lactate concentration and the subsequent release of carbon dioxide, as a result of bicarbonate buffering of lactic acid hydrogen ions accompanying lactic acid dissociation, drives the ventilation. Protocols which involve large incremental increases in exercise intensity artificially accelerate ventilation.

Excessive respiratory frequency (f_R) may be indicative of physical inactivity or of abnormalities in breathing mechanics, however, it should be noted that children generally attain a much higher f_R at maximal exercise than adults (commonly in excess of 60 breaths·min^{-1} which declines with age).[26] In comparison to adults, children have a higher ratio of f_R to tidal volume (V_T) indicating reduced ventilatory efficiency. Ventilatory efficiency is related to the ratio of air that participates in gas exchange (i.e., alveolar ventilation) and that which does not (i.e., dead space). Without the more invasive assessment of blood gases, ventilatory/perfusion mismatch or ventilatory efficiency can be estimated using the $\dot{V}_E/\dot{V}O_2$. Although not without limitation as a measure of ventilatory efficiency, good correlations between the degree of pulmonary blood flow maldistribution and the slope of elevation for $\dot{V}_E/\dot{V}O_2$ have been shown, supporting the use of this variable as a marker of ventilation/perfusion mismatch and indicative of pulmonary and cardiac disease.[27,28]

For every litre of oxygen consumed, children display a higher $\dot{V}_E$ than seen in adults, indicating that the metabolic cost of ventilation in children is greater (i.e., higher $\dot{V}_E/\dot{V}O_2$). This suggests that there is some maturation of the ventilatory control mechanisms during childhood and adolescence. Excessively high $\dot{V}_E/\dot{V}O_2$ is a common feature in conditions such as pulmonary and cardiac failure. Trained children have high maximal $\dot{V}_E$ values, which are thought to reflect a greater utilisation of the lung capacity, as opposed to differences in lung dimensions. Consequently, ventilatory reserve at maximum is reduced in child athletes in comparison to untrained children.[29]

Cardiovascular Function

Oxygen uptake and arteriovenous oxygen difference (a-v O_2 dif) determine pulmonary blood flow and in the absence of any abnormal shunt, pulmonary blood flow mirrors systemic flow, or cardiac output. Therefore $\dot{V}O_2$ can be expressed as the product of cardiac output ($\dot{Q}$) and a-v O_2 dif.

Methodological and ethical limitations have hindered our understanding of $\dot{Q}$ and stroke volume (SV) during progressive exercise, particularly at maximum. Nevertheless, data for both adults and children are consistent. Increases in $\dot{Q}$ with increasing exercise parallel the rise in $\dot{V}O_2$. During exercise in an upright position SV rises progressively to values 30-40% greater than resting and reach this level at 40-60% of peak $\dot{V}O_2$. Stroke volume then plateaus despite further increases in exercise intensity, with subsequent rises in $\dot{Q}$ relying exclusively on HR.[30-32] Increases in peak $\dot{V}O_2$ following training have been attributed to increases in stroke volume, which is augmented as a result of increases in pre-load, decreases in after-load and cardiac enlargement.[33,34]

Heart rate can be used in the calculation of oxygen pulse ($\dot{V}O_2$ / HR), which has been used as a surrogate noninvasive marker of combined cardiopulmonary oxygen transport. A high oxygen pulse at a given workload represents circulatory changes such as a widening of the a-v O_2 dif and increased $\dot{Q}$, and indicates a fitter individual.[2] A reduced oxygen pulse may indicate a condition that reduces stroke volume such as left ventricular dysfunction, or reduced oxygen extraction at the cellular level such as anaemia or hypoxaemia.[2]

HR rises in an almost linear manner during progressive exercise before tapering-off to its maximum (HR_{max}). HR_{max} is subject to wide individual variations but during youth, it is independent of age, maturation, sex and aerobic fitness and healthy children normally attain a maximum value around 200 beats.minute^{-1}. It should be noted that the HR_{max} value is dependent on both the ergometer used and the exercise protocol.[12,13,35]

Arteriovenous oxygen difference reflects a range of factors including blood haemoglobin concentration, blood volume, muscle blood flow, aerobic enzyme activity, and mitochondrial density. It therefore serves as an index of the haematological components of oxygen delivery and the oxidative mechanisms of the exercising muscle. Unfortunately estimating a-v O_2 dif from $\dot{V}O_2$ and estimates of $\dot{Q}$ is methodologically flawed. Recent work using cardiac magnetic resonance imaging markers of cardiac size and thoracic impedance measure of peak $\dot{Q}$ has shown higher a-v O_2 dif in prepubertal boys compared to girls.[36] These data open up the hypothesis that there are sex differences in peripheral factors such as muscle fibre type which enhance boys' cardiopulmonary function. This work provides much impetus for future research into muscle cellular activity during exercise in children.

Peak Oxygen Uptake

Published peak oxygen uptake data for Hong Kong children and adolescents are limited, however a number of studies are available which report laboratory assessed data for girls and boys and these are summarised in Table 4. The treadmill has been the ergometer of choice for all except one of the reported studies. The peak $\dot{V}O_2$ values reported from the one available cycle ergometer CPET are similar to those determined on the treadmill. However, it should be noted that these values were pre-training values for a small group of highly motivated boys who were about to embark on a rigorous 8-week training programme and are unlikely to be representative of the normal population.

The development of aerobic fitness with age has been studied extensively in European and North American children, but no longitudinal data are currently available for Hong Kong Chinese children. McManus et al.[37] have shown that absolute peak $\dot{V}O_2$ values for younger Chinese girls and boys are considerably lower than those for similarly aged Caucasian children, tested using a similar treadmill protocol; however, by adolescence values are similar. Using Armstrong and Welsman's[23] regression equations absolute values were 17% and 31% lower than predicted for the under 10 year-old and 10 to 13 year-old boys respectively, and 19% and 23% lower for the under 10 year-old and 10 to 13 year-old girls respectively. At the oldest age reported, predicted absolute peak $\dot{V}O_2$ values were only 3% different from measured values for both sexes.

Peak $\dot{V}O_2$ is strongly correlated with body size and coefficients describing its relationship with body mass or stature typically exceed r=0.70. Thus, much of the age-related increase in peak $\dot{V}O_2$ reflects the overall increase in body size during the transition from childhood through adolescence into young adulthood. The conventional use of mass-related values, however, might have clouded our understanding of peak $\dot{V}O_2$ during growth. Rather than removing the influence of body mass, ratio scaling 'overscales' favouring light children and penalising heavy children. The underlying theory of this has been addressed extensively elsewhere and compelling arguments have been presented to question the validity of simple ratio scaling to adequately remove the influence of body mass from size-dependent performance measures such as peak $\dot{V}O_2$.[44] Several studies have generated data illustrating how inappropriate ratio scaling has led to misplaced interpretation of physiological variables whereas studies in which the use of more appropriate means of controlling for body size have provided new insights into peak $\dot{V}O_2$ during growth.[23]

When a log-linear model was applied to data on Chinese children, in boys an increase from pre-puberty to puberty, followed by a plateau in peak $\dot{V}O_2$ was apparent.[37] This is in keeping with interpretations of growth and maturation of peak $\dot{V}O_2$ in Caucasian boys.[45] In contrast, Hong Kong Chinese girls showed little variation in adjusted peak $\dot{V}O_2$ until late puberty when it rose. This is quite a different pattern to that seen in Caucasian girls who show a rise in early puberty and then a plateau in peak $\dot{V}O_2$.[45]

In the Caucasian child even when body size has been accounted for, maturational differences have been found to persist and this needs to be considered during comparative interpretation of peak $\dot{V}O_2$ data. Armstrong and Fawkner illustrate the magnitude of the maturational effect upon peak $\dot{V}O_2$ in British children and show how this effect can be attenuated when maturity-related changes in fat-free mass are considered, but they remain nonetheless.[46] The growth spurt in boys' body mass primarily relates to gains in skeletal muscle, with fat mass remaining relatively stable. Girls on the other hand experience less dramatic increases in skeletal muscle, but a continuous rise in fat mass. As such boys' peak $\dot{V}O_2$ is consistently higher than girls' from late childhood. This pattern is apparent in the data presented in Table 4 with Hong Kong Chinese boys' peak $\dot{V}O_2$ consistently greater than that of girls. Without longitudinal data a thorough understanding of the maturational changes in peak $\dot{V}O_2$ is not possible for the Hong Kong Chinese child. Until such data are available, when comparisons of peak $\dot{V}O_2$ are sought matching groups on the basis of sex and maturation is prudent.

There are regular media reports of the declining aerobic fitness of Hong Kong youngsters. Such reports are misleading given they are based upon measures of performance and not accurate measurement of aerobic fitness.[47] To date, there are no laboratory studies available investigating secular changes in peak $\dot{V}O_2$ in Hong Kong children. In contrast there is ample evidence that body mass, and more specifically overweight, is showing a secular increase in this population.[48] It is therefore most likely that mass adjusted peak $\dot{V}O_2$ will show a decline over time if the denominator (e.g., body mass) continues to increase without concomitant increases in absolute peak $\dot{V}O_2$. Serial population-based measurement of peak $\dot{V}O_2$, appropriately controlled for body mass and maturation, will verify temporal changes in aerobic fitness, but at the time of this review these data do not exist for Hong Kong.

Submaximal Markers of Cardiopulmonary Function

Submaximal exercise responses can be extrapolated from maximal data or can be acquired during a submaximal CPET. Such data provide extremely valuable information about cardiopulmonary function which is of direct relevance to a child's day-to-day activities. The benefits of submaximal information are significant when one considers that children rarely exercise to maximum. The efficiency of the cardiopulmonary system to exercise of a similar intensity to normal day-to-day activity is clinically important when making recommendations for activity participation and for monitoring whether increased activity results in increased cardiopulmonary function. Submaximal variables afford alternative insight into cardiopulmonary function such as quantification of the response time of the cardiopulmonary system to the demands of a given amount of work; an indication of the degree of hypoxia, the efficiency of ventilation and degree of ventilation-perfusion mismatching. A brief review of some of the submaximal parameters available from respiratory gas analysis follows.

Ventilatory Threshold

Ventilatory threshold (VAT) is the most frequently used submaximal measure and allows the detection of oxygen uptake at the onset of lactate acidosis. It has been proposed as a useful and alternative index of aerobic fitness in children, particularly valuable for those for who are unable to give a maximal effort.[49] The VAT reflects the highest exercise intensity that can be performed at the expense of oxidative energy production, therefore reflecting the oxidative potential of the working muscle.

VAT can be determined in a number of ways including an abrupt increase in (i) ventilation, (ii) ventilatory equivalent for oxygen, (iii) the respiratory exchange ratio or (iv) the end-tidal pressure of oxygen. These increases must be accompanied by no increase in (i) the ventilatory equivalent for carbon dioxide or (ii) the end-tidal pressure for carbon-dioxide. Figure 2 provides a graphical illustration of the VAT determined by the ventilatory equivalents method.

Since ventilation can be erratic and lag behind $\dot{V}O_2$ in certain conditions e.g., obese patients or those with airway obstruction, an additional method avoiding the use of ventilation in the calculation is the V-slope method.[50] This involves regressing carbon dioxide production against oxygen uptake. Most metabolic carts offer computerised detection of VAT from the V-slope method. This is based upon the intersection of two regression lines explaining $\dot{V}CO_2$ as a function of $\dot{V}O_2$ and is illustrated in Figure 3. The VAT is chosen from the point at which the residual sum of squares is minimised.

One of the advantages of the VAT is that it is a submaximal marker and is believed to be more responsive to change than maximal parameters. Several studies have

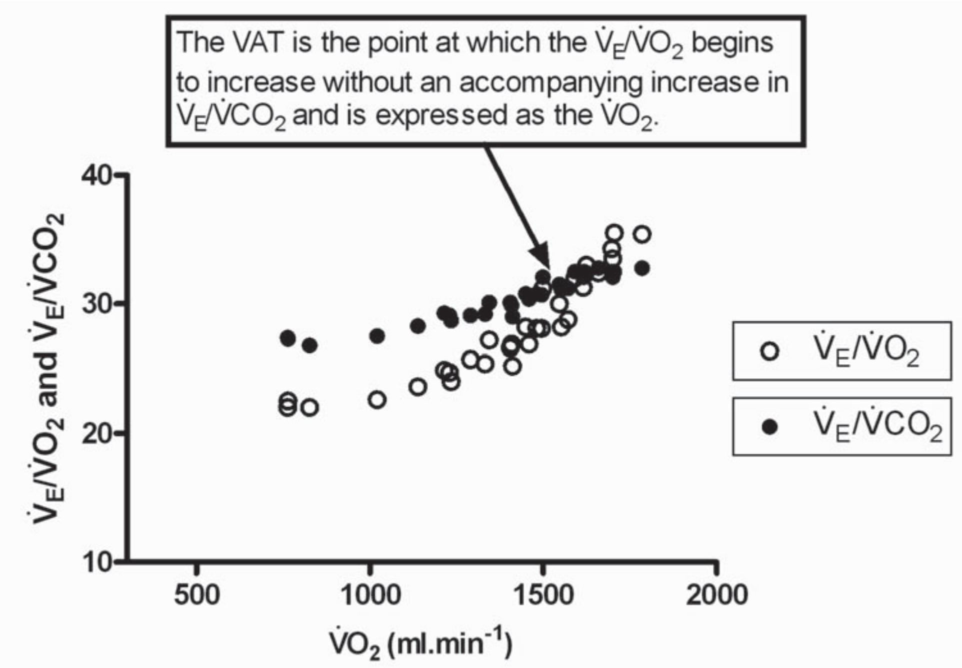

Figure 2 Ventilatory anaerobic threshold determined using the ventilatory equivalents method.

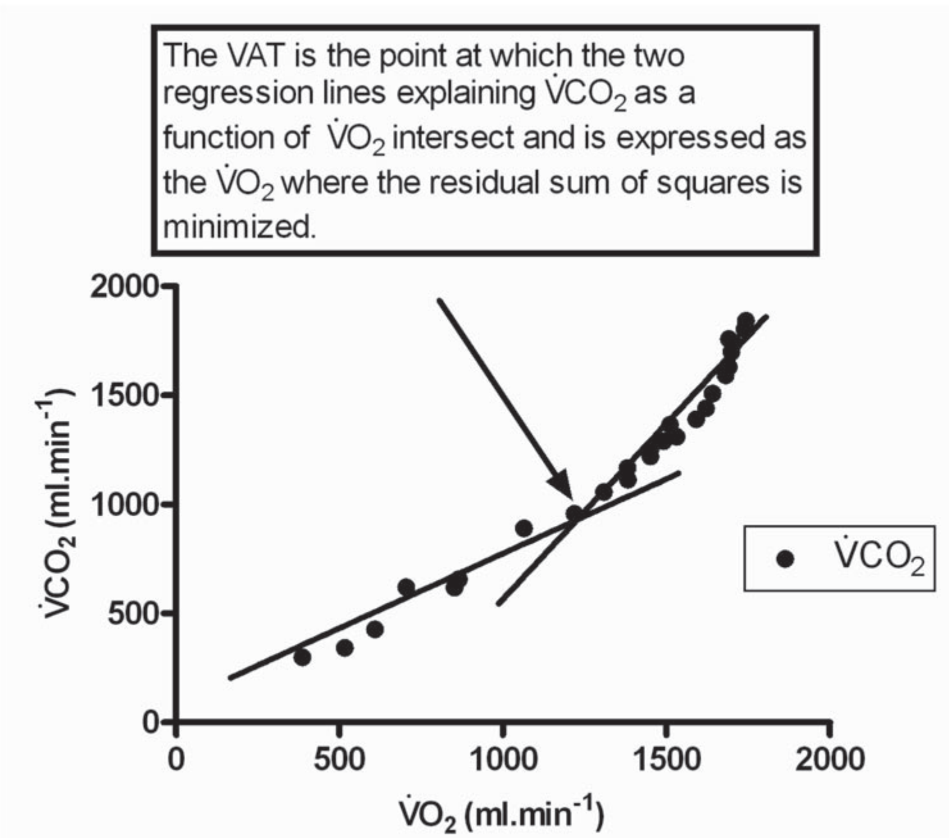

Figure 3 Ventilatory anaerobic threshold determined using the V-slope method.

indicated higher VAT values in trained children. For example, Mahon and Vaccaro[51] found VAT, expressed as a percentage of peak $\dot{V}O_2$, increased from 67% to 74% in 10 to 14 year old boys following aerobic training. Although McManus et al.[38] reported a non-significant increase in VAT expressed as a percentage of peak $\dot{V}O_2$ from 76% to 82% following interval training in Hong Kong Chinese boys, the absolute and mass-adjusted (ratio-scaled) peak $\dot{V}O_2$ at which VAT was recorded increased significantly in the trained boys only.

VAT has been used to help distinguish exercise limitations in patient groups. For example, it has been shown to be lower than normal values in children with congenital heart disease, irrespective of the type of heart defect.[52] In Hong Kong Chinese children VAT has been used to evaluate cardiopulmonary function 6 months after contracting Severe Acute Respiratory Syndrome (SARS). A trend was found for a decreased VAT in patients with abnormal high resolution computed tomography (HRCT) findings compared to those with normal radiological presentation. VAT increased significantly by 15 months post-SARS in those with abnormal HRCT scans indicating improvements in aerobic capacity over time.[53]

Although a useful submaximal marker, it must not be forgotten that VAT is not always possible to detect, with failure rates of approximately 18% in children.[49] Using an approach which plots ventilatory variables against $\dot{V}O_2$ rather than time improves detection rates and therefore the V-slope method is often the preferred mode of calculation.

Oxygen Uptake Efficiency Slope

The oxygen uptake efficiency slope (OUES) is a relatively newer and less frequently used submaximal index of cardiopulmonary function during exercise. It represents the rate of increase in $\dot{V}O_2$ in response to minute ventilation and is thought to indicate how effectively oxygen is extracted by the lungs and used at the periphery.[54] The OUES is described by the following exponential function:

$$\dot{V}O_2 = a \text{ x } \log \dot{V}_E + b$$

Where a represents the rate of increase in $\dot{V}O_2$ in response to $\dot{V}_E$ and b is a constant.

The greatest advantage of the OUES is that it is not affected by exercise intensity and appears to be independent of the protocol, again valuable for testing children who are unable to give a maximal effort. Its usage in clinical groups is becoming more common, for example, obese children have been found to have a lower OUES than lean children.[55] Likewise, Chinese children who contracted SARS were found to have significantly lower OUES values than controls 6-month after positive diagnosis of the disease. Two factors which lower OUES are metabolic acidosis and increases in physiological dead space. In the youngsters who had contracted SARS, an absence of hyperventilation suggested metabolic acidosis was absent, however, the higher $\dot{V}_E/\dot{V}O_2$ noted in the patient group with abnormal HRCT findings suggested the elevated OUES was likely indicative of lung perfusion impairment.[53]

Oxygen Uptake Kinetics

The measurement of respiratory variables using breath-by-breath analysis has allowed the study of oxygen uptake kinetics. Analysis of oxygen uptake kinetics provides an indication of energy utilisation at the muscular level and may prove very useful in understanding the interplay between cardiopulmonary and metabolic processes during exercise.[56] This review will provide only a brief overview of oxygen uptake kinetics and readers are encouraged to refer to previous reviews for a more detailed understanding of the child's oxygen uptake kinetic response.[57,58]

The oxygen uptake kinetic response to moderate intensity exercise (i.e. exercise below the VAT) has been described by three phases which are illustrated in Figure 4. At the onset of exercise from rest a delay in $\dot{V}O_2$ is followed by a rapid rise in $\dot{V}O_2$. This first phase, or cardiodynamic phase, lasts about 15s and is thought to represent the sudden increase in cardiac output at the onset of exercise.[59] Phase I

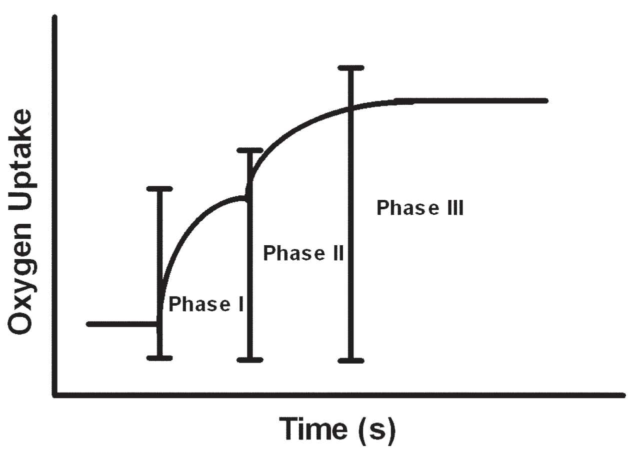

Figure 4 Graphical representation of the oxygen uptake kinetic response after the onset of moderate intensity (below VAT) constant rate exercise.

is independent of $\dot{V}O_2$ at the muscle and reflects increases in pulmonary blood flow. Oxygen uptake then increases exponentially toward steady state (phase II), representing $\dot{V}O_2$ at the muscle.[56] The speed of the phase II or primary response is described by a time constant (τ), representing the time taken (s) to achieve 63% of the change in $\dot{V}O_2$. The attainment of a steady state signifies Phase III.

Despite the potential value of the oxygen uptake kinetic response its measurement is complicated by the large inter-breath variation in oxygen uptake in children. This reduces the confidence with which kinetic parameters can be estimated and necessitates the measurement of multiple identical transitions, which can then be aligned to allow the calculation of a mean response across transitions.[58]

To date, only one study with children has provided this level of measurement rigour and these data support the idea that the child's oxygen uptake kinetic response is significantly quicker than that of the adult. Fawkner et al showed the phase II time constant was on average 9s faster in boys than men and 5s faster in girls compared to women.[60] Additionally, oxygen deficit was relatively lower in the children in this study. This faster increase in $\dot{V}O_2$ to steady state and smaller relative oxygen deficit suggest a lower anaerobic metabolic contribution during Phase II and likely reflects children's enhanced capacity for oxidative phosphorylation during moderate-intensity exercise.[58]

Discussion of the complex $\dot{V}O_2$ kinetics of heavy exercise (i.e. exercise above VAT but below critical power) is beyond the scope of this review (see Fawkner and Armstrong[58] for details). However, the results of a recent longitudinal study of prepubertal children's $\dot{V}O_2$ kinetics response to heavy exercise are consistent with the presence of a developmental influence on the muscles' potential for oxygen utilisation and therefore support an enhanced oxidative function during childhood.[61]

Concluding Remarks

Exercise gas exchange studies providing both maximal and submaximal data not only assist in the recognition of cardiopulmonary dysfunction, but also help qualify the cardiovascular, metabolic and/or ventilatory contribution to exercise limitation. The limited data available for Hong Kong Chinese children and adolescents highlights the importance of population specific normative values. Cross-sectional data suggest a pattern of development that is quite distinct from Caucasian children, particularly for younger, less mature Hong Kong Chinese children. Only longitudinal studies will confirm these developmental patterns and further work is needed to reveal the relative importance of other aspects of the oxygen delivery pathway to the development of peak $\dot{V}O_2$ during childhood and adolescent growth in Chinese children. The future of the CPET lies in the integration of exercise testing with the array of non-invasive techniques now available.

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