Anaerobic and Aerobic Capacities of Children

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This paper deals with the measurement of aerobic and anaerobic power in children, and how these capacities are affected by growth and training. The type of tests available, the selection of ergometer, establishment of criteria for determining whether a maximal value has been attained, and the limitations of the various expressions of maximal values are discussed. Aerobic capacity, when expressed in liters per minute, has been observed to increase with growth; when expressed relative to body weight, aerobic capacity has been shown to remain the same or decrease with age. Anaerobic capacity increases with age no matter how the values are expressed. Limited evidence suggests that training during prepubescence does not increase aerobic capacity beyond that expected from growth. Several methodological limitations of longitudinal studies are examined.

The body's ability to do mechanical work is dependent upon the splitting of adenosine triphosphate (ATP) to release energy for muscle contraction. The cells constantly resynthesize ATP by one of three methods: (a) from limited reserves of phosphagens, (b) from glycolysis whereby pyruvate is converted to lactic acid, and (c) from the conversion of substrates to carbon dioxide and water through the Krebs cycle and the electron transport system. The first two methods are considered anaerobic processes, since oxygen is not immediately needed for energy production, whereas the third method is aerobic.

The intensity and duration of an activity will determine which of these energy systems will supply the energy for work. For example, short-distance running dashes are anaerobic activities whereas a marathon is considered aerobic. Maximal capacities of the aerobic and anaerobic systems are theoretically linked to performance of specific activities. Maximal aerobic power is also used as an indicator of cardiovascular capacity. In children, studies have been conducted to determine the effect of growth on these two metabolic systems and to compare children's values with those of adults.

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This paper will deal primarily with how the maximal capacity of the anaerobic and aerobic energy supply systems are measured in children and how they are affected by growth and training.

Aerobic Power

Maximal aerobic power (the maximal amount of energy the aerobic metabolic system can produce per minute) is measured by the maximal volume of oxygen ($\text{VO}_2$) that can be consumed by the body per minute (maximal or peak oxygen uptake). Aerobic power is measured in children, as it is in adults, by a graded exercise test during which oxygen uptake ($\text{VO}_2$) is determined. Peak oxygen uptake is commonly assessed in children either on a cycle ergometer or a treadmill. The latter is preferred when dealing with younger children, especially those 7 years old or younger, since on the cycle (a) local muscle fatigue may limit performance prior to attainment of maximal $\text{VO}_2$ values, (b) younger children and disabled children may not be able to keep a regular cadence even with a metronome, and (c) limited attention span may prevent the child from maintaining the required pedaling rate for the duration of the test (3). In younger children (preschoolers), walking and running are more natural and a treadmill test can yield a considerably higher peak oxygen uptake than with cycling (26).

However, since children in Europe learn to cycle early in life, many longitudinal studies done in these countries have used cycle ergometers. If a cycle is used, certain modifications of the ergometer must be considered. Most children 8 years or older can use the models used for adults. For younger children either a special pediatric model must be used or the pedal crank and handlebar and seat height have to be modified (3).

A variety of exercise protocols are available for children. One study performed with 10- to 12-year-old boys found that on the treadmill, walking protocols elicited significantly lower and more variable values than did various running protocols (29). A walking protocol has been used with mentally retarded children, with a continuous or intermittent protocol eliciting similar values (31). Peak values obtained on the cycle ergometer have been found to be consistently lower than $\text{VO}_2$ values obtained with walking or running protocols (3, 18).

Theoretically, the most objective criterion for determining whether a subject has performed maximally is the plateau or leveling off in oxygen consumption at high exercise intensities. Sheehan et al. (29) used a relative criterion for plateau (a rise in oxygen uptake less than the mean increase per submaximal workload increment minus twice the $SD$) and found running protocols (vs. the walking protocol) elicited the greatest percent of subjects attaining a plateau. Krahenbuhl and Pangrazi (17) found that 20 of 21 boys met the plateau criterion when using an absolute criterion of less than a 2.1 ml/kg/min increase in oxygen uptake.

Although several investigators have had success in attaining plateau criteria with children, other investigators (6, 23) have found that achieving a plateau in children is not realistic (plateau attained in less than 40% of maximal tests performed) and that a leveling off of oxygen uptake is not a prerequisite for maximal performance.

When the plateau criterion is not attained, additional criteria that have been used to determine maximal effort include the following:
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1. Attainment of a heart rate that is 95% of age-predicted HR max or the leveling off of HR despite of an increase in power output;
2. Respiratory exchange ratio (RER) greater than 1.0 (children may have lower RER values at maximal power outputs compared with adults, possibly because children generate less lactate and excess CO₂ (24, 29);
3. Appearance of extreme forced ventilation or other subjective signs of exhaustion;
4. Lactate levels of about 6–7 mmol/liter for 7- and 8-year-olds, or 4 mmol/liter for 5- and 6-year-olds.

A major problem with testing children is their short attention span and unwillingness to perform under the degree of physiological strain necessary to achieve a true maximal value. For children, therefore, motivation may be the limiting methodological problem. Innovative methods of motivation and creative use of testing protocols are probably the most critical aspect of achieving true maximal values.

As has been suggested with adults, the term “peak oxygen uptake” may be the more appropriate term than “maximal VO₂.” Peak VO₂ values obtained among various studies may greatly depend on the protocol chosen, and this must be kept in mind when comparisons are made among studies. The choice of protocol for the graded exercise test depends on what is most comfortable and familiar for the subjects and investigators, and on the measurements to be obtained. The critical attribute of the aerobic capacity determination is that the values produced are reproducible and that local muscle fatigue does not cause the test to terminate prior to exhausting aerobic mechanisms.

**Anaerobic Power**

Anaerobic power is measured in tests whereby a supramaximal test is performed for a minute or less. Two tests have commonly been employed. The Margaria step running test, in which a child runs up several steps at maximal speed, determines peak mechanical power of legs in a period of approximately a second. Power is calculated based on body weight, vertical distance, and time. The test has some limitations: It requires some skill, cannot be applied to disabled children, and arm performance cannot be measured (3).

A test that has been frequently used to assess anaerobic performance is the Wingate Anaerobic Test (WAT). In this test the child pedals or arm cranks on a cycle ergometer at a maximal speed against a constant supramaximal mechanical force (approximately two to four times the maximal aerobic capacity) for 30 seconds. The test, developed at the Wingate Institute for Physical Education and Sport in Israel during the mid- and late-1970s, is based on the assumption that anaerobic performance is a local rather than a systemic characteristic and is constructed to assess the ability of a muscle group to perform short supramaximal exercise. In such a task the limiting factor is not the oxygen transport system but rather the ability to convert anaerobic chemical energy to mechanical energy (3).

The Wingate Test is feasible for use with both healthy and disabled children as young as 6 years of age. When younger children are being tested, consider-
ation must be given to adapting the cycle ergometer by shortening the pedal crank length. The two most common measures determined from the Wingate Test are,

1. Peak power—the highest mechanical power produced during any 3- to 5-sec period. Originally, peak power was assumed to reflect alactic (phosphagen) anaerobic processes, but subsequent research has shown that muscle lactate rises to extremely high values as early as 10 seconds into the test (4). Therefore peak power is most accurately used to reflect the ability of the limb musculature to produce high mechanical power in a short time.

2. Mean power—the average power sustained throughout the 30-sec period. Although many have used mean power as a measure of anaerobic capacity, the developers of the Wingate Test state that mean power reflects the ability of the muscle groups to sustain extremely high power output, that is, endurance (4).

The choice of the resistance setting is extremely important when trying to elicit the highest peak and mean power on the Wingate Test. In a study done on 13- to 14-year-old children (9), it was discovered that the optimal force is lower for children than for adults and lower for girls than for boys. Since it was also shown that the optimal load for peak power measurement is considerably higher than that for maximizing mean power, it is evident that a single test cannot be optimized for both kinds of power measurements.

Warmup has been shown to enhance mean power performance in children (4). In terms of motivation, although studies have not been done with children, it is suggested that motivation techniques be standardized for all subjects. It is also necessary to explain to the child the nature and importance of the test.

Several studies have shown the Wingate Test to give reproducible data for able-bodied boys and girls and for children with cerebral palsy and muscular dystrophy (4, 8). In addition, the test results are reproducible under several environmental conditions and are not affected by varying states of hydration. Therefore the Wingate Test seems to be a practical (since in its simplest form only a stop-watch and a cycle ergometer are needed) and reliable test that can be performed in field situations where climate cannot be controlled.

There is no established "gold standard" that measures mechanical power and local endurance against which to validate the WAT. Construct validity has been demonstrated for boys ages 10 to 15 since sprint athletes scored significantly higher than long-distance runners on the Wingate Test (32). This logical relationship was not established for the girls, however. Scores on the Wingate Test have also been found to be sensitive to anaerobic training (12, 25).

While the Wingate Test is performed using predominately anaerobic metabolic sources, only about 50% of the variance in anaerobic type task can be accounted for by performance on it. Tharp et al. (32) examined 50-yard dash and 600-yard run times and found that when expressed in absolute power terms, the Wingate Test scores were not strong predictors of performance times. Therefore it seems that these tasks entail skill and other fitness components that are not measured by the Wingate Test.
Aerobic Power and Growth

Historically, the effects of growth and development on peak oxygen uptake were based on values obtained from cross-sectional studies, mainly Robinson's data obtained in 1938 and Astrand's 1952 study (1, 24). Krahenbuhl et al. (18) plotted the values of approximately 65 cross-sectional and longitudinal studies that were done with untrained children (see Figure 1). If a cycle ergometer was used in a study, the peak oxygen uptake value was multiplied by 1.075. When regression equations were calculated, absolute \( O_2 \) uptake was found to increase across chronological age for boys and girls. Using the regression lines as a guide, Krahenbuhl et al. concluded that values for boys and girls are similar until approximately age 12.

It should be noted that these regression lines were developed on data points that are both independent measures (cross-sectional studies) and repeated measures (longitudinal studies). Regression analysis assumes that each point can vary to the same degree. This may lead to under- or overestimation of predicted values when using these regression equations.

\[
\dot{V}O_{2\text{max}} (l \cdot min^{-1})
\]

- **males**
- **females**

\[
y = 0.859 - 0.013x + 0.010x^2
\]

\[
y = 3.539 - 0.915x + 0.104x^2 - 0.003x^3
\]

**Figure 1** — Relationship in children between \( \dot{V}O_2 \) \(_{\text{max}} \) (\( l \cdot min^{-1} \)) and chronological age. Data points are mean values from approximately 65 separate studies. All group data were corrected to treadmill values (bicycle \( \dot{V}O_2 \text{ max} \times 1.075 \)) (18). (Reprinted with permission of MacMillan Publishing Company from "Developmental aspects of maximal aerobic power in children," by G.S. Krahenbuhl et al. Copyright © 1985 by American College of Sports Medicine.)
Since absolute peak O₂ values increase with growth in children, a relative rather than an absolute expression must be used to compare peak aerobic power in children who differ in body size and mass. The most common expression for comparative purposes is to express peak O₂ uptake values relative to body weight. Krahenbuhl et al. (18) found that there is a minimal age-related change in peak oxygen uptake in boys from ages 6 to 16. In girls the peak O₂ uptake, expressed relative to body weight, was found to decline beginning at age 6 (see Figure 2). A proposed explanation is that the decline may reflect an increase in body adiposity and therefore a relative decline in lean body mass.

Although expressing peak O₂ uptake relative to body weight is the most commonly used expression for relating aerobic power to maturity and growth, it is not the best theoretical choice, since differences in body composition are not considered. In addition, the relationship of weight with peak O₂ has been shown to have varying levels of importance at different ages. Cunningham et al. (5) found that explained variance in peak oxygen uptake due to weight ranged from 50 to 70% in children ages 9 to 15 years.

Since the correlation coefficient between peak oxygen uptake (expressed in liters per minute) and body weight is approximately 0.70 (13), dividing by mass does not express the aerobic capacity totally independent of body weight. Katch and Katch (14) caution that since ratio scores expressed relative to body mass may not express oxygen uptake independent of body weight, the use of ratio scores can result in spurious correlations, for example when examining the relationship between oxygen uptake and work performance.

Figure 2 — Relationship between \( \dot{V}O_2 \) \(_{max} \) (ml \( \cdot \) min\(^{-1} \cdot \) kg\(^{-1} \)) and chronological age (18). See legend for Figure 1.
If the purpose of a study is to examine cardiovascular efficiency, then the use of peak oxygen uptake expressed relative to fat-free weight has been proposed as the best indicator in adults (7). While expressing oxygen uptake values relative to fat-free weight has no predictive value for performance, it does attempt to remove the confounding influence of body size and body composition on oxygen uptake. Cunningham et al. (5) have suggested that weight and fatness alone can account for approximately 80% of the variance of peak oxygen values in children of similar age. In reviewing various investigations in which VO₂ values have been expressed relative to fat-free weight (FFW), the limiting factor appears to be the methods used to determine body composition. As the accuracy of body fat determination increases in children, expressing peak oxygen values relative to FFW may prove useful as an index of cardiovascular efficiency, assuming the same assumptions hold for children as for adults.

Dimensional scaling has been suggested as an alternative approach for determining growth related changes in peak VO₂. The use of a linear dimension (i.e., height) to control for growth changes is conceptually preferable to body weight (2). Although some investigators maintain that height is the best index of body size that reflects the growth process (2), it has been suggested that there is no practical advantage in using height or any exponential of it over the use of body weight or fat-free mass for growth related comparisons (3, 18, 30).

There is clearly a need for further understanding and standardization of the units used in expressing peak oxygen uptake. Investigators must give more a priori consideration to the choice of expressing peak VO₂ values and cannot assume that dividing by body weight completely removes the effect of growth on peak VO₂. The choice of expression must take into account the bias, the advantages and disadvantages of each method, and whether the expression used is the one most related to the purpose of the study.

Growth and Anaerobic Power

In their review, Inbar and Bar-Or (12) indicate that two cross-sectional studies have examined age related changes in anaerobic power using the Margaria Test. Both studies found that, whether expressed in absolute terms or relative to body weight, peak anaerobic power increases with age. Similar results have been observed with the data collected from the Wingate Institute in Israel and McMaster University in Canada using the Wingate Test. Increases with chronological age were found in (a) absolute mean power, (b) mean power relative to body weight, (c) absolute peak power, and (d) peak power relative to body weight for both boys and girls (3).

The limited anaerobic capacity of children as compared to adults has been associated with the observation that children have lower lactate production (3, 12, 19) during exercise. This could be due to children having lower activity levels of phosphofructokinase and other glycolytic enzymes, lower sympathetic activity (which has been hypothesized to increase lactate removal because of increased blood flow to the liver), and a shorter half-time increase in oxygen uptake prior to reaching steady state. In addition, children have been shown to have (a) lower resting concentration of glycogen, (b) lower rate of anaerobic utilization of glycogen, and (c) higher ventilatory thresholds (3, 12).
An additional indicator of anaerobic capacity is the degree of acidosis at which the muscle can still contract. Children do not reach as high a level of acidosis during maximal exercise as do adolescents or young adults (3). The concentration and breakdown of adenosine triphosphate and creatine phosphate are probably at the same level in children and adults (3).

In summary, whether children have different maximal aerobic capacity as compared to adults is still debatable, with the conclusion being based on how one expresses peak VO\(_2\) values. However, children have been found to have lower anaerobic capacities, whether scaled to body weight, height squared, or lean body mass. Figure 3 shows a common scale of values expressed as percentage of the value attained at 18 years of age. Peak VO\(_2\) relative to body weight is observed not to change or even to decrease, while there is a growth related increase in anaerobic performance.

**Performance**

Peak VO\(_2\) has been extensively studied because of its role in limiting the capacity to perform aerobic tasks in adults and because it is considered to be the best single

![Figure 3](image-url)  
**Figure 3** — Development of aerobic and anaerobic characteristics. Mean values are percentages, taking the value at 18 years as 100% (3). (Reprinted with permission from Springer-Verlag Inc. from Pediatric Sports Medicine for the Practitioner, by O. Bar-Or. Copyright © 1983.)
index of health related fitness. However, peak VO$_2$ may not be the major limiting factor in the child’s capacity to perform aerobic activities (i.e., endurance fitness). In a study in which 10- and 11-year-old boys performed a 1200-m run taking more than 5 minutes (a task considered mainly aerobic), the run times had the same correlation with anaerobic measures (mean power and peak power from the Wingate Test) as with peak VO$_2$ (25). This may indicate that children are not “metabolic specialists” and that, as opposed to adults, aerobic and anaerobic capacities covary in this age group.

In another study, 10- to 14-year-old boys and girls ran 2000 m (a task taking more than 10 minutes) (22). When several variables were entered into a forward selection multiple regression analysis, mean power from the Wingate Test accounted for almost 60% of the variance in run time, with peak VO$_2$ accounting for only an additional 7%. In a review of the effects of physical activity on cardiopulmonary fitness in children, Wells (33) stated that the younger the child, the more difficult it is to predict performance from peak VO$_2$ data.

Even though children have the same value for peak VO$_2$ related to body weight, it does not mean they can perform weight-bearing activities as well as adults. Bar-Or (3) points out that children at the same numerical value have a lower aerobic reserve. Children are mechanically inefficient, and running at the same pace costs them a far greater percentage of their maximal aerobic capacity. It is possible that for children, endurance fitness has more to do with other variables such as ventilatory threshold, ventilatory efficiency, submaximal VO$_2$, submaximal heart rate, O$_2$ transients, and/or anaerobic capacities (11).

**Training**

There are several excellent review articles regarding children and training (18, 27, 33). The majority of studies on training in children have concentrated on circumcision or pubescent children. In the half dozen or so training studies that were done with children ages 12 years or younger and that had a control group (see Figure 4), four studies found no significant increase in peak VO$_2$ (expressed relative to body weight) over the control groups. The three studies that found significant increase in peak VO$_2$ had been done on children ages 8 to 12 years. It is imperative that a control group be included in training studies and that children are completely familiarized with the treadmill, since an 8% increase in peak VO$_2$ was found in 6- to 7-year-old children after a 10-day familiarization period (28).

In several longitudinal studies (16, 21, 26) in which children were followed over several years, differences in absolute peak VO$_2$ between active and inactive children were not observed until after they had reached structural maturity (peak height velocity). Results of these longitudinal studies appear to support the hypothesis that activity during the preadolescent period had minimal if any effect on peak oxygen uptake and that adolescence is the critical period. There are some problems in these longitudinal studies. In two of them (16, 21) only a few subjects were studied. Kobayashi et al. (16) studied 56 boys, with only 7 trained subjects being measured from prepubescence. Mirwald et al. (21) studied 25 7-year-old boys for 10 years (14 active, 11 inactive subjects). Cunningham et al. (5) point out that the results may be subject to confounding influences of differences in rates of maturity between active and inactive groups (see Figure 5). Although aligned on peak height velocity, boys who are early maturers may show marked-
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CONTROL GROUP

Figure 4 — Effect of training on peak oxygen uptake. (Data for individual studies obtained from review article by Sady [27]).

likely different cardiovascular responses to exercise. Peak VO₂ values for late maturers at a given maturation age prior to peak height velocity (PHV) have been found to be higher than for early maturers. The inactive subjects in one study (21) were also the later maturers based on skeletal age, which means that maturation age might have confounded the results attributed to inactivity.

Another series of studies also show that values found with inactive groups may be confounded by maturation age. Rutenfranz (26) compared longitudinal data of Norwegian boys and girls with longitudinal data collected on children from West Germany. When comparisons were made across chronological age, Rutenfranz concluded that the differences between Norwegian and German children in oxygen uptake were due to a more physically active lifestyle in Norway. When the development of peak VO₂ was reexamined as a function of maturation (age at PHV), peak aerobic power increased during prepubescent years mainly as an effect of growth in body size. Interpreting the same data across maturation age, Rutenfranz now suggests that peak VO₂ values represent optimal values brought about mainly by normal growth in body size, with little or no additional effects of physical activity (26).

Another problem with some longitudinal studies is that a mixture of cross-sectional and longitudinal data have been included in the analysis (20), or reference groups have not been followed up to or after the growth period (16). However, there seems to be sufficient evidence that peak VO₂ values of prepubescent
children do not respond in a similar fashion to training as compared to pubescent children. Since maturation age is so variable (covering ages 9 to 16), it is imperative that research done on children 9 years or older identify maturation age so that interpretation of results are not confounded by varying responses of prepubescent and pubescent children.

Few studies have examined training effects on the anaerobic capacity of children. Anaerobic training studies done on children have shown improved scores on the Wingate Test (12, 25) or have shown increases in the concentration of glycogen, PFK activity, and the rate of glycogen utilization in 11- to 15-year-old boys (10).

Yet to be achieved is an understanding of the separate effects of growth, development, and training on the anaerobic and aerobic capacities of children. Longitudinal studies are needed that (a) use larger, more diverse samples, (b) evaluate maximal and submaximal aerobic and anaerobic responses, and (c) assess accurately both activity levels and body composition.

Kemper (15) suggests that to control for the effects of growth, habituation, secular trends, and changes in sophistication of methods, longitudinal studies should include a multiple design. The design would involve (a) a classical longitudinal study whereby the same individual is followed across several years, (b) a classical cross-sectional design in which children of varying ages are measured.
in the beginning year of the study, and (c) a classical time-lag study in which, during each year of the study, children of the same age are measured.

Summary

Maximal aerobic capacity is measured in children with a graded exercise test during which VO₂ is determined. The choice of ergometer, the establishment of criteria for determining whether a maximal value has been attained, and the various expressions of these maximal values have been discussed in this paper. Maximal anaerobic capacity is determined by measuring the peak mechanical power or the total amount of mechanical work done during a supramaximal test that lasts a minute or less. The Wingate Anaerobic Test (WAT) has been discussed in detail.

Absolute aerobic capacity as well as absolute and relative anaerobic capacities have been observed to increase with growth. Aerobic capacity, however, when expressed relative to body weight, remains the same or even decreases with age. Limited evidence suggests that training during prepubescence does not increase peak VO₂ values beyond that attributed to growth. However, increases in anaerobic metabolic systems and in WAT scores with training, beyond that expected from growth, have been observed.

Due to methodological limitations as well as the limited amount of studies performed with prepubescent children, several questions regarding maximal aerobic and anaerobic capacities remain unanswered or need further investigation. Emphasis of research should be concentrated on what will help children maintain a healthy lifestyle and to identify those children who are below the norm and most in need of specific programs to increase their health related fitness.

References


