Cardiovascular, Ventilatory, and Metabolic Parameters during Exercise: Differences between Children and Adults

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With the growing popularity and emphasis on the benefits of physical conditioning in children, it is important to understand the physiological aspects of exercise in the pediatric population. Children should not be seen as "miniature adults"[1]; they are unique and have singular traits at each phase of growth. Development of the skeletal muscle, nervous, and endocrine systems largely determines their physiological and metabolic limits under physical exertion[1,2]. Currently, there is a growing interest in research on growth and physiological development in children and adolescents, and consequently on the mechanisms involved in the cardiorespiratory and metabolic behavior of the pediatric population during physical exercise. In fact, certain authors[2-5] attribute the different physiological and metabolic responses observed in children during physical exercise to their level of biological maturation, since as they grow, they also develop in almost all functional capacities.

In an elegant study carried out by Vinet et al[3], it was noted that prepubertal children have the lower values of cardiac output at peak exercise when compared to young adults. As to cellular metabolism, several studies have observed that children have less efficient glycolytic activity during physical exercise compared to adults[1,5-7]. During the pubertal growth spurt, important hormones (somatotropin, growth factors similar to insulin, and sexual steroid hormones) are released into the blood stream[1,2]. There is an increase in lean body mass, and this change in body composition has a positive influence on the development of physical capacities and performance during puberty.

Therefore, several aspects of biological adaptations to exercise in children and adolescents should be considered. Which physiological alterations in response to exercise occur with age, when children and adolescents have the same absolute energy expenditure in performing their tasks? Are there significant differences in cardiovascular, ventilatory, and metabolic responses to different demands (submaximal or maximal) of exercise in the growing individual? (Tab. 1)

We present various studies that show the possible morphofunctional mechanisms that characterize cardiovascular, ventilatory, and metabolic responsiveness during physical effort observed in children.

Key words

Children, physical exercise, cardio circulatory, ventilatory and metabolic response.

Cardiovascular aspects

In cardiovascular parameters such as heart rate (HR), stroke volume (SV), cardiac output (Q), and the arterial-mixed venous O_2 difference (a-v), the pediatric population has a distinct behavior both at the submaximal and maximal levels of effort relative to that observed in adult congeners. [2,3,8,9] Possible causes may be 1) smaller heart and blood volume[2,3,8]; 2) greater stimulation of peripheral chemoreceptors[8]; 3) lower levels of circulating catecholamines[10]; 4) lower responsiveness of beta-adrenergic receptors [11] and 5) difference in the adjustment of thermoregulation mechanisms[12,13].

Heart rate

The heart rate, an important parameter utilized in the control of the intensity of physical training, shows an exacerbated response in children. [2,3,8,9,12] For Vinet et al[3], this great chronotropic activity observed in children for a given work demand is due to a compensation mechanism related to a smaller heart volume, smaller blood volume, and subsequently, a smaller stroke volume (Fig. 1). Turley & Wilmore[8] on the other hand, attribute this exacerbated chronotropic response to greater activation of the peripheral chemoreceptors relative to a larger accumulation of muscle metabolism subproducts. According to these authors, this increased afferent stimulation observed in children may be linked to the recruitment of a smaller absolute quantity of muscle tissues for an equal work demand, imposing a greater mechanical load per unit of muscle.

Accordingly, studies comparing the chronotropic response in adult individuals for the same work demand found a greater heart rate for exercises performed by small muscle groups compared to those using large muscle groups[14,15]. Turley[16], however, in his investigation to analyze the metaboreflex influence on chronotropism during isometric exercise, observed that the muscular metaboreflex influence on the chronotropic response is similar in children and adults.

For Bar-Or[12], the greater chronotropism observed in children for a given submaximal exercise intensity may be partly related to differences in body temperature modulation. Children have a reduced evaporative capacity to dissipate body temperature since they depend more on convection

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Received on 10/14/05 • Accepted on 12/08/05

Cardiovascular variables	Submaximal exercise		Maximal exercise	
	Children	Adults	Children	Adults
HR (bpm)	↑↑	↑	↑↑	↑
SV (ml/beat)	↑	↑↑	↑	↑↑
Q (l/min)	↑	↑↑	↑	↑↑
(a-v) O2	↑↑	↑	↑	↑↑
Ventilatory variables				
RR (breaths/min)	↑↑	↑	↑↑	↑
TV (ml/min)	↑	↑↑	↑	↑↑
VE (l/min)	↑	↑↑	↑	↑↑
VE/VO2	↑↑	↑	↑↑	↑
RER	↑ or ↑↑	↑↑	↑	↑↑
Metabolic variables	Children		Adults	
[CP]	↔		↔	
Tissue [Glycogen]	↓		↑	
[PFK] and [LDH]	↓		↑	
PFK and LDH activity	↓		↑	
[ ] and oxidative enzyme activity	↑		↓	

↑ *increase;* ↓ *decrease;* ↔ *similar; CP – creatine phosphate; PFK – phosphofructokinase;* LDH – *lactate dehydrogenase. Adapted from Boisseau & Delamarch[1]; Haralambie[43]; Vinet et al[3]; Rowland & Cunningham[4]; Turley & Wilmore[8].*

Table 1 - Comparison of cardiovascular, ventilatory, and metabolic variables between children and adults at submaximal and maximal levels of exercise

and radiation[12,13]. The actual loss of heat by these routes (convection and radiation) increases the redistribution of blood flow to body surface area at the expense of the central blood volume, instigating a shift towards an increased heart rate (cardiovascular drift) in order to maintain a given cardiac output.

Stroke volume

The stroke volume, i.e., the quantity of blood ejected from the left ventricle during a systole, shows curvilinear kinetics in children during progressive physical exercise[3,9,17,18], which is the same behavior seen in adults[19,20]. In an important study using Doppler and bidimensional echocardiography, Rowland et al[17], attributed this curvilinear profile (plateau) to several mechanisms. These mechanisms are 1) peripheral vasodilatation playing an important role in the initial SV rise (smaller after load); 2) increased heart rate with greater workloads, maintaining a stable SV (plateau) and left ventricular diastolic dimension and 3) a greater responsiveness in contractility (inotropism) helping to maintain the SV relative to the greater work loads.

For Nottin et al[18], however, the curvilinear behavior observed in children is due to a combination of the pre-load, after load, and myocardial contractility. According to the authors,[18] the main finding of this investigation was the fact that children and adults use similar mechanisms for SV adaptation in face of progressive physical exercise. In spite of similar SV kinetics between children and adults, the pediatric population shows an attenuated inotropic response, and consequently, lower resting and exercise (submaximal or maximal) values for SV in comparison to those observed in their adult congeners[2,3,8,9] (Fig. 2). Possible mechanisms suggested for this attenuated systolic activity in children are 1) smaller cardiac and blood volumes[2,3,8]; 2) lower levels of circulating catecholamines[10]; 3) lower responsiveness of beta-adrenergic receptors[11] and 4) lower inotropism of myocardial cells[21].

For Rowland et al[9], the smaller SV observed in children both at rest and during physical exercise is closely related to morphological aspects (smaller cardiac volume and smaller

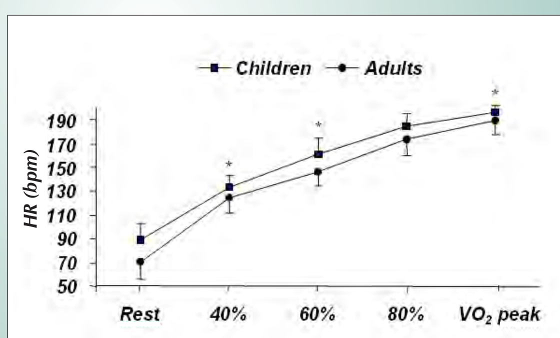

Fig. 1 - *Heart rate kinetics in children and adults during progressive physical exercise. (*) P < 0.05- difference between the groups. Adapted from Vinet et al[3].*

blood volume) and not to functional aspects, in agreement with what had been postulated by other studies[11,21]. According to the authors, there are no indications that myocardial contractility is smaller in children and tends to increase with physical maturity. The authors came to this conclusion by observing identical values between children and adults for the systolic time interval (myocardial contractility marker) and left ventricular ejection fraction, quantified by means of echocardiography.

Cardiac output

Cardiac output, the product of the heart rate by the stroke volume, may be defined as the volume of blood ejected from the left ventricle per minute[22]. In fact, this variable presents smaller values for all relative intensity levels of exercise in the pediatric population[3,8,23] (Fig. 3). According to Vinet et al[3], the lower cardiac output values observed in children for a given work demand are primarily related to the smaller volumes of blood and heart. Turley & Wilmore[8] observed that the cardiac output for a given work demand (VO_2) was 1.0 to 2.9 l/min lower in children relative to that seen in adults when they exercised on the bicycle and on the treadmill, respectively. The authors[8] attributed these findings to a lower cardiac volume, as well as a lower stroke volume.

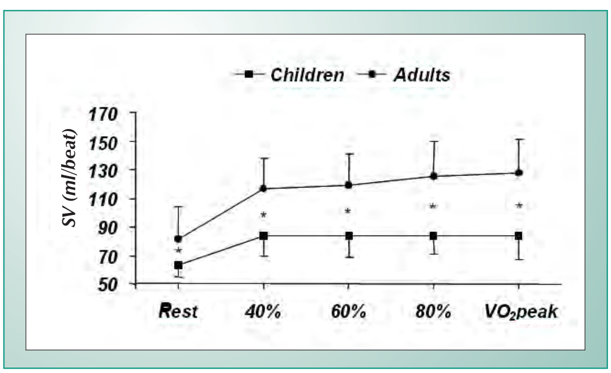

Fig. 2 - Stroke volume kinetics in children and adults during progressive physical exercise. (*) $p < 0.05$- difference between the groups. Adapted from Vinet et al[3].

On the other hand, in cross-sectional studies Miyamura et al[23], observed that the maximal cardiac output increased from 12.5 to 21.1 l/min in boys between ten and twenty years of age, respectively. According to Malina & Bouchard[2], the dimensions of the heart increase over time until biological maturation along with body mass growth, and this enlargement is related to an elevation of both the stroke volume and cardiac output.

(a-v) O_2 difference

The arterial-mixed venous O_2 difference may be defined as the difference in oxygen content between arterial and mixed venous blood[22]. This physiological variable reflects the efficiency of oxygen extraction peripherally by metabolically active tissues. In fact, for a given absolute submaximal exercise intensity (VO_2), children present greater A-VO_2 differences in order to compensate the smaller cardiac output

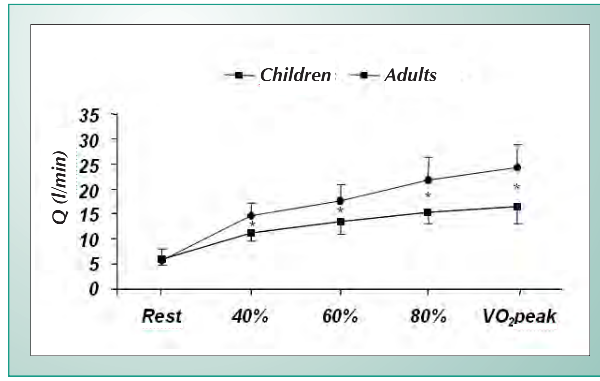

Fig. 3 - Cardiac output kinetics in children and adults during progressive physical exercise. (*) $p < 0.05$- difference between the groups. Adapted from Vinet et al[3].

compared to that of their adult counterparts[2,8,24] (Fig. 4). For Turley & Wilmore[8], the greater efficiency in peripheral oxygen extraction observed in children is related to 1) an intensification of oxygen release by hemoglobin because of a greater accumulation of tissue metabolism co-products, as well as an increased production of heat per unit of muscle (Bohr effect); and 2) a greater vasodilation of arterioles that irrigate the active muscles with a possible increase of muscular blood perfusion. First of all, children burn more energy per kilogram of weight in order to perform the same work as adults (they have a poor energy economy during exercise); this is why a child produces a greater quantity of heat relative to his corporal mass than an adult in order to perform the same amount of work[2]. This mechanism, known as the Bohr Effect, is a crucial factor for the rise in oxygen release by hemoglobin[22,25].

In children exercising on an cycle ergometer, Koch[26,27] observed greater muscular blood perfusion compared to that observed in adults for the same work demand. Nevertheless, for maximal levels of work, values in the pediatric population were lower[3,9]. Rowland et al[9], observed smaller (a-v) O_2 differences at peak exercise in children relative to those seen in adults, with results of 13.9 and 17.2 mL/100 mL, respectively. According to the authors[9], this finding may be partly explained by the smaller oxygen concentration in arterial blood reflected by lower levels of circulating hemoglobin, as was observed in children[2,8].

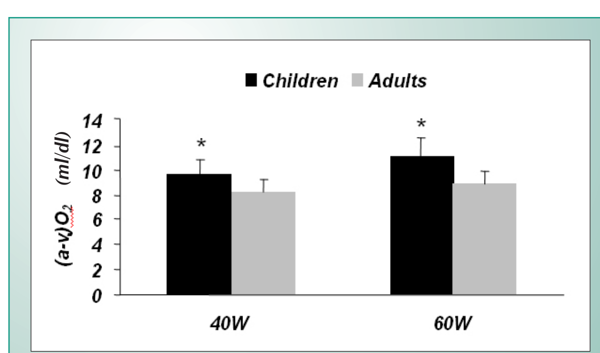

Fig. 4 - Arteriovenous oxygen differences between children and adults at different absolute submaximal exercise intensities. Adapted from Turley & Wilmore[8].

Ventilatory aspects

Volumes and static pulmonary capacities, as well as tidal volume, inspiratory reserve volume, expiratory reserve volume, forced vital capacity, residual pulmonary volume, and total lung capacity, including dynamic pulmonary volumes such as forced expiratory volume and maximal voluntary ventilation, provide signs of the progress and functional efficiency of the respiratory system growth of a child[2]. These volumes and capacities show accentuated changes with age, with an increase of all lung volumes until growth is completed[2,22].

Changes in these volumes and capacities, however, correspond to changes in maximal ventilation that may be attained during exhaustive exercise; this maximal ventilation is called maximal expiratory ventilation (MVmax), or maximal minute ventilation[22]. For example, cross-sectional studies show that the mean MVmax is approximately 40 l/min for boys four to six years of age, and increases to 110 to 140 l/min at full maturity. These alterations are associated to the growth of the pulmonary system that accompanies the general patterns of growth in the child[22]. For Malina & Bouchard[2], the increase in volumes and lung capacities, both static and dynamic, is intimately related to the child's growth in stature.

Minute ventilation

Minute ventilation (MV), i.e., the product of respiratory rate (RR) by the tidal volume (TV), can be defined as the volume of air dislocated by the lungs per minute[22]. In fact, ventilatory variables such as RR, TV, and MV are closely linked to the child's anthropometric characteristics, particularly body mass and stature[28]. In pre-puberal children, Rowland & Cunningham[4] observed that with age, the RR shows a progressive drop and the TV shows a linear climb, stabilizing at physical maturity, both for a given submaximal and maximal work intensity.

When children are submitted to a given absolute submaximal intensity of exercise, for example 60 watts on a cycle ergometer, the intensity of the ventilatory response is exacerbated relative to that seen in adults, and progressively decreases with age[2,4]. Over a period of five years, Rowland & Cunningham[4] noted a progressive decline in the ventilatory equivalent of oxygen (VE/VO_2) variable, both for a given absolute submaximal intensity and for peak effort (Fig. 5).

Part of the explanation for this poorer ventilatory efficiency seen in the pediatric population is related to the mechanics of ventilation. In fact, Lanteri & Sly[29] found that, with the advancement of age, there is a progressive increase in lung tissue complacency and a decrease in resistance to air flow. On the other hand, Springer et al[30], and Gratas-Delamarche et al[31], attributed the lower ventilatory efficiency seen in children to neurohumoral mechanisms. According to these authors, children have a lower peripheral chemoreceptor set-point for modulation of arterial PCO_2, resulting in exacerbated hyperpnea. These data are reflected by higher values of VE/VO_2 for the same metabolic demand, compared to their adult counterparts.

For maximal workloads, however, children have smaller minute ventilation values. Rowland & Cunningham[4] observed a positive correlation between the chronological age and the maximal minute ventilation. Prioux et al[32], however, noted a direct relationship between an increase in lean body mass and maximal minute ventilation. Rutenfranz et al[33], observed a positive relationship between stature and maximal minute ventilation in children eight to seventeen years of age.

There is no doubt that the higher values of MV at peak of exercise reached by the pediatric population with increasing age are related to the levels of somatic maturation, and show a direct association with the growth of the pulmonary system[2,32,33].

Metabolic aspects

Anaerobic metabolism

The production of anaerobic energy is important, since many of the activities carried out by children involve explosions of energy expenditure or sprints, contrary to moderately intense activities maintained for longer periods[2]. A child's energy needs during exercise, therefore, cannot always be supplied by the predominance of oxidative properties in active muscular tissue, when anaerobic energy production mechanisms should kick in to allow these activities to be carried out.

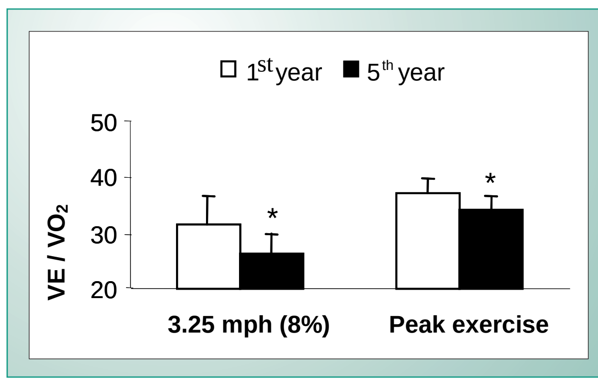

Fig. 5 - Values of MV/VO2 at absolute submaximal and maximal levels of exercise between the 1st and 5th year of investigation. (*) P < 0.05- difference between the years. Adapted from Rowland & Cunningham[4].

In fact, the pediatric population has a smaller anaerobic capacity in comparison to that seen in adults[1,2,5-7], and it is not possible to identify an isolated morphological, physiological, or biochemical factor that determines this lower performance capacity in anaerobiotic conditions. On the contrary, the lower anaerobic efficiency seen in children comes from the interaction of these factors. Possible explanations for this attenuated anaerobic capacity include 1) differences in the pattern of recruitment of motor units[1,34]; 2) differences in muscle fiber types[1,35,36]; 3) lower tissue levels of muscle glycogen[1,37-39]; 4) reduced activity of key glycolytic enzymes such as phosphofructokinase (PFK) and lactate dehydrogenase (LDH)[1,2,6,7,38] and 5) reduced muscular glycogenolytic activity by covalent modification[40]. Evidence suggests that part of the improvement observed in the anaerobic performance in children as they grow is due to an increase in myelination of the motor cortex nervous fibers[22], thus improving coordination and activation of motor units[34].

In his study, Atomi et al[35], observed that the percentage of oxidative (type I) muscle fiber area is larger in children before puberty, compared to that of glycolytic (type II) muscular fibers. Additionally, there is evidence in cross-sectional studies that children possess a higher percentage of oxidative muscle fibers than glycolytic muscle fibers relative to adults, suggesting the possibility of a growing participation of gycolytic fibers with age[36]. In another spectrum, studies[37,38] have shown that tissue content of muscular glycogen in children is about 50% to 60% the concentration found in adults.

In children with an average age of 11.6 years, Eriksson & Saltin[39] observed an intramuscular glycogen concentration of about 54 mmol/kg, and in children with average ages of 12.6, 13.5, and 15.5 years, the levels of this energetic substrate were 70, 69, and 87 mmol/kg, respectively. In another investigation, Eriksson et al[37], found a catalytic activity approximately 50% lower for the phosphofructokinase (PFK) enzyme (PFK) in pre-puberal children compared to adults. Children have lower rates of muscular glycogen conversion into lactate for rephosphorylation of the limited ATP storage during aerobic and anaerobic activities, corroborating the glycolytic immaturity that has been observed in them. Part of the explanation for this reduced glycogenolytic activity is related to a lower release of epinephrine, which could be associated with low sympathetic nervous activity, implying an attenuated activation of muscle glycogenolysis by covalent modification[9].

Quantification of the influence of biological maturational on a child's energy metabolism could be analyzed through phosphorus-31 nuclear magnetic resonance spectroscopy. In an elegant study, Zanconato et al[40], noted that children present a smaller rise in the inorganic phosphate/creatine phosphate (Pi/PC) ratio and a smaller drop in the intramuscular pH compared to adult counterparts, suggesting that the pediatric population has a lower capacity for ATP rephosphorylation activation through anaerobic routes (alactic and lactic) during high intensity physical exercise.

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Aerobic metabolism

Aerobic metabolism, also called oxidative metabolism, is directly related to the capacity of metabolically active tissues (skeletal muscle) to supply exercise demands for ATP by means of the coupled reactions of the Krebs cycle and electron transport chain that are processed in mitochondria[22]. Factors that characterize a high peripheral tissue oxidative capacity are[41] 1) a greater quantity of type I skeletal muscle fibers; 2) a greater mitochondrial density; 3) a greater concentration and catalytic activity of oxidative enzymes and 4) a greater capillary density.

According to what was covered before, different studies[1,35,36] have noted a high percentage of type I fibers in children suggesting a greater peripheral oxidative capacity compared to their adult counterparts. In his investigation, Haralambie[42] observed that the oxidative enzymes of the Krebs cycle (isocitrate dehydrogenase, fumarase and malate dehydrogenase) showed exacerbated catalytic activity in children when compared to adults. In the same study, the author noted a difference in the phosphofructokinase/isocitrate dehydrogenase ratio between children and adults (0.884 and 1.633, respectively), indicating a greater oxidation rate of piruvate per part in the pediatric population.

Using procedures of phosphorus-31 nuclear magnetic resonance spectroscopy, Zanconato et al[40], suggested that children have an high rate of oxidative phosphorylation during intense exercise, attributing this finding to both a greater capillary density and a greater mitochondrial density. Nevertheless, Bell et al[43], identified a similar relationship between mitochondrial and myofibril volumes among pre-puberal children and adults.

Using the analysis of expired gases (indirect calorimetric) as an indirect form of inferring the mixture of macronutrients being metabolized during physical exercise at a stable rhythm (steady state)[1], Rowland et al[44], observed that for a given absolute submaximal intensity of exercise, pre-puberal children had significantly lower values of RER (respiratory exchange ratio) relative to adults. These data suggest that children are better adapted to utilization of fat as an energy-providing source during exercise at a stable rhythm, which could be associated with a greater metabolic apparatus, that is, greater mitochondrial density and greater concentration and activity of oxidative enzymes[1,22].

Final considerations

While still in their period of growth, the morphological and functional characteristics of children are in a process of development. Many of these maturation-dependent characteristics respond in different ways to physiological stress induced by physical exercise. It is important to consider these singularities of the juvenile organism; a correct understanding of the physiological and metabolic aspects during physical exercise is of utmost importance for an appropriate prescription of physical training. In this way, a program of physical training for a pediatric population deserves attention and much care in its formulation.

Potential Conflict of Interest

No potential conflict of interest relevant to this article was reported.

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