Pulmonary function and respiratory response during exercise in children

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Abstract This short review discusses the development of respiratory function and pulmonary ventilation during exercise in children. Children have a lower lung capacity than adults because of their smaller chest and relatively narrow airways. Respiratory muscle strength (RMS), which is evaluated by maximal expiratory (PEmax) and maximal inspiratory (PImax) mouth pressure, is also lower in children than adults. RMS tends to be higher among children who exercise, in particular, in those who swim. Minute pulmonary ventilation during exercise is lower in children, whereas respiratory frequency and tidal volume to vital capacity are higher, suggesting that exercising children have lower ventilatory efficiency and higher ventilatory effort than adults. Thus, expiratory flow limitation (expFL) caused by mechanical constraints, observed in adult females with small chest walls and in endurance athletes with high ventilatory demands, is also observed in most children. Although expFL limits hyperventilation and leads to exercise-induced arterial hypoxemia (EIAH) in adults, only a third of children show EIAH. Physically trained children with high maximal oxygen uptake tend to have a greater expFL, which could be one of the mechanisms responsible for EIAH.

Keywords: children, respiratory muscle, ventilation, exercise

Introduction

The healthy human lung has considerable ventilation capacity in reserve during exercise. In fact, even during intense exercise, minute ventilation ($V_{E}$) does not reach maximal voluntary ventilation (MVV). Thus, $V_{E}$ and lung capacity have not generally been considered as limiting factors for aerobic capacity$^{1)$. However, several studies have reported that highly trained endurance athletes and fit females develop exercise-induced arterial hypoxemia (EIAH), which limits maximal oxygen uptake ($VO_{2\text{max}}$)$^{2-5)$. The subjects of these studies showed suboptimal gas exchange as a result of inadequate hyperventilation during intensive exercise. This inadequate hyperventilation was caused by reduced respiratory chemosensitivity$^{2) or mechanical constraints that induced the expiratory flow limitation (expFL)$^{5)$. It is hypothesized that the ventilatory response in children is limited by lung capacity and mechanical respiratory function, which accounts for the lower aerobic capacity compared to adults.

Higher $V_{E}$ levels require higher effort in breathing (higher respiratory muscle activity). During maximal exercise, the oxygen consumption by respiratory muscles is more than 15% of $VO_{2\text{max}}$)$^{6}$, and the respiratory muscles demand compromises in the blood flow to other active muscles$^{7-8)$. Furthermore, the respiratory muscles fatigue after exhaustive exercise$^{9,10)$, Thus, increased respiratory muscle strength (RMS) enhances exercise performance and exercise tolerance$^{11)$. Consequently, the development of RMS in children is likely to be important for fitness and aerobic capacity. The aim of this short review is to focus on the characteristics of pulmonary function development and discuss the role of ventilatory response to gas exchange during exercise in children.

Growth of pulmonary function

Vital capacity (VC) and forced vital capacity (FVC) are lower in children compared to adults$^{12)$. In growing children, lung volume develops almost linearly with height rather than with age$^{13)$. The peak velocity of increases in VC and FVC occur after the development of the peak height velocity$^{14)$. In a study of children aged 0-14 years, Thurlbeck$^{12)$ found that, for a given age and stature, lung capacity was greater in boys than in girls.

RMS is assessed by mouth pressure at maximal inspiratory (PImax) and maximal expiratory (PEmax) effort at total lung capacity (full inspiration) and residual volume (full expiration), respectively. It is a simple and reliable parameter to determine the status of pulmonary function. In healthy adults, there is large individual variation in normal values of PEmax and PImax, the magnitude of which relates to height and age$^{15,16)$. Body builders have been shown to have a higher RMS than endurance athletes$^{17)$; however, in another study, no significant difference was found between untrained adults and endurance athletes$^{18)$. It has been reported that PI_{max} and PE_{max} in children develop according to growth$^{19)$. Swain et al.$^{20)$ reported that,
even in prepubescent children (7.6-11.4 years of age), total lung capacity, FVC, and RMS were significantly higher in boys compared to girls. Plmax and PEmax correlate with height and weight rather than with age. In a study conducted by Wilson et al. on 370 healthy boys and girls (11 years of age, Caucasian), Plmax and PEmax were found to be significantly correlated with weight. In our laboratory, we investigated Plmax and PEmax among healthy elementary school children and college students (unpublished data). This study was approved by the local Ethics Committee. Fig. 1 shows Plmax and PEmax for children aged 6-9 years (younger children: n = 15), 10-12 years (older children: n = 13), and college students (n = 28). Both Plmax and PEmax were higher in the older children than in the younger children. In the children of both age groups and in the college students, Plmax and PEmax were higher in males than in females. Thus, both Plmax and PEmax were significantly correlated with age, height, and weight, which is in agreement with the findings of previous studies. Moreover, Plmax and PEmax were significantly correlated with FVC (p < 0.05; r = 0.7), and the correlation was stronger (a higher r value) than that with both height and weight. In children, the development of RMS can be explained by the development of lung capacity rather than by increases in height and weight. Santos et al. compared Plmax and PEmax in 7 to 8-year-old boys who were divided into 3 categories: untrained, swimmer, and indoor soccer player. They found that swimmers had a higher Plmax and PEmax than both indoor soccer players and untrained boys, and there was no significant difference between the results for soccer players and the boys who did not train. In our data, Plmax and PEmax were approximately 1.5 times higher in children who swam compared with those who did not, supporting the results of Santos et al. The breathing mechanism necessary during swimming might be different from other sports. Swimmers have to breathe deeply and quickly between strokes and have to overcome the pressure of the water. It is likely that the respiratory muscles are specifically trained because of the forced breathing during swimming.

Mechanical constraints in ventilatory response during exercise in children

Because children have a smaller lung capacity than adults, maximal Ve during exercise in children is lower than that in adults. The respiratory frequency (fR) during exercise is higher, whereas the ratio of tidal volume (VT) to VC (VT/VC) is lower in children than in adults. Ve increases with the increase in VT, and fR decreases with age. Children show a higher Ve at a given rate of VO2 or carbon dioxide elimination (VCO2) compared...
with adolescents and adults\textsuperscript{23-27}, suggesting that children show relative hyperpnea with high frequency, shallow breathing. However, the absolute value of \( V_{E} \) is lower in children than in adults. In adults, expFL caused by mechanical constraints is observed among trained endurance athletes and active females. In these subjects, adequate hyperventilation is limited relative to ventilatory demand, gas exchange is impaired, and EIAH develops. Therefore, it has been proposed that EIAH could also develop in children as a result of mechanical constraints.

Laursen et al.\textsuperscript{28} found that in active prepubescent girls (11 ± 1.6 years old; \( VO_{2\text{max}} \); 43.7 ± 7.1 ml/kg/min), there was no significant arterial desaturation at maximal exercise [range of oxygen saturation (SaO\(_2\)) 94%-98%]. Conversely, Nourry et al.\textsuperscript{29} reported that in 29% of active prepubescent children (\( VO_{2\text{max}} \); 51.4 ± 1.1 ml/kg/min in boys and 40.2 ± 1.8 ml/kg/min in girls) there was significant arterial oxyhemoglobin desaturation during maximal exercise. VT, \( f_{R} \), and \( V_{E} \) were not significantly different between hypoxic and non-hypoxic children. However, hypoxic children (SaO\(_2\) 91.3 ± 0.8%) had a smaller FVC and smaller estimated breathing reserve (BR = MVV \( - V_{E} \) at maximal exercise/MVV) during maximal exercise compared with non-hypoxic children (SaO\(_2\) 95.7 ± 0.2%). Therefore, EIAH develops in children with a higher aerobic capacity (\( VO_{2\text{max}} > 43 \text{ ml/kg/min} \)), as a result of a lower lung capacity and breathing reserve associated with ventilatory demand, rather than as a result of the absolute \( V_{E} \) level.

In a series of studies by Nourry et al.\textsuperscript{30,31}, more than half of the children studied developed expFL during heavy exercise. Fig. 2 shows representative flow-volume loops for children with expFL (Fig. 2A) and without expFL (Fig. 2B). During exercise, children with expFL had a higher inspiratory residual volume and lower end-expiratory volume associated with FVC compared to non-expFL children, despite similar VT and \( V_{E} \) in both groups. The breathing strategy was different between the children with expFL and without expFL, but neither group developed EIAH. Furthermore, Swain et al.\textsuperscript{30} found that the prevalence of expFL during exercise was similar in prepubescent boys and girls (19/20 in boys and 18/20 in girls), despite a higher \( VO_{2\text{max}} \) (35.4 ± 7.5 ml/kg/min in boys vs. 29.5 ± 6.6 ml/kg/min in girls) and a higher FVC (2.2 ± 0.4 l/s in boys vs. 1.9 ± 0.3 l/s in girls) in the boys. However, in a comparison between aerobically-trained prepubescent children (\( VO_{2\text{max}} \); 50.4 ± 4.0 ml/kg/min) and untrained children (\( VO_{2\text{max}} \); 36.1 ± 4.9 ml/kg/min), although the occurrence of expFL did not differ between the groups, compared with untrained children, trained children showed lower BR to MVV and breathed at a higher lung volume at maximal exercise. These results suggest higher ventilatory mechanical constraints among trained children compared with untrained children. Moreover, trained children showed significantly greater arterial desaturation and more dyspnea compared with untrained children. Therefore, in trained children, inadequate hyperventilation in response to increased ventilatory demand caused by mechanical constraints can, at least in part, explain the development of EIAH.

**Conclusion**

In summary, children have a smaller lung capacity and lower RMS than adults. RMS develops with age, height, and lung capacity. Participating in sports, particularly swimming, enhances the development of RMS. Children show relatively higher levels of hyperventilation in response to metabolic demand during exercise compared to adults. Consequently, mechanical constraints to ventila-
tory capacity are observed in most children; and in trained children, mechanical constraints contribute to the development of EIAH. However, further research is required to understand the relationship between respiratory muscle function and exercise ventilation in children.

Conflict of Interests

The authors declare that there is no conflict of interests regarding the publication of this article.

References