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Ventilatory responses at submaximal exercise intensities in healthy children and adolescents during the growth spurt period: a semi-longitudinal study

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Abstract

Purpose To identify the changes of ventilation ($\dot{V}_E$), tidal volume (V_T) and respiratory frequency (fr) at different incremental step test intensities during maturation of children and adolescents.

Methods A semi-longitudinal study was conducted on 68 healthy untrained boys and girls aged 11–17 years. The subjects were separated into three distinct age groups. $\dot{V}_E$, V_T and fr parameters were evaluated annually during 3 years by modifying incremental step test intensities according to ventilatory threshold (V_{Th}) level (30, 60 and 90% of $\dot{V}_{O_{2max}}$). Absolute and relative values of ventilatory responses were analyzed and compared according to age and developmental phase.

Results (1) Height, weight, lean body mass and vital capacity increased significantly from 11 to 17 years of age. (2) $\dot{V}_{O_{2max}}$, $\dot{V}_E$, and V_T increased during maturation even when exercise intensity changed, especially from 11 to 15 years of age. On the other hand, fr showed a decreasing trend.

Conclusion Increases of V_T are the main reason for $\dot{V}_E$ increases during maturation of children. fr decreased independently of total body mass during maturation. $\dot{V}_E \cdot kg^{-1}$ was stable despite intensity variations. $V_T \cdot kg^{-1}$ increased significantly from 11 to 15 years then stabilized at 17 years. Lean body mass seems to explain the evolution of $V_T \cdot kg^{-1}$ during maturation.

Keywords Semi-longitudinal study · Submaximal exercise · Breathing pattern · Children · Adolescents · Boys · Girls

Abbreviations

BM	Total body mass	
CO ₂	Carbon dioxide	24
fr	Respiratory frequency	25
fr _{max}	Maximal respiratory frequency	26
HR	Heart rate	27
O ₂	Oxygen	28
R	Respiratory exchange ratio	29
T _E	Expiratory time	30
T _{Emax}	Maximal expiratory time	31
T _I	Inspiratory time	32
T _{Imax}	Maximal inspiratory time	33
T _{TOT}	Total respiratory time	34
T _{TOT}	Maximal total respiratory time	35
T _{TOTmax}	Maximal total respiratory time	36
VC	Vital capacity	37
$\dot{V}CO_2$	Respiratory dioxide output	38
$\dot{V}_E$	Ventilation	39
$\dot{V}_{Emax}$	Maximal ventilation	40
$\dot{V}O_2$	Oxygen uptake	41
$\dot{V}O_{2max}$	Maximal oxygen uptake	42
V_T	Tidal volume	43

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44	V_{Tmax}	Maximal tidal volume
45	V_{Th}	Ventilatory threshold

46 Introduction

AQ2 The increased supply of oxygen (O_2) to the muscles is essential during physical exercise (Zhang et al. 1993). During the first phase of this process, is the transport of O_2 to the alveoli through ventilation ($\dot{V}_E$) (Calbet and Lundby 2009). $\dot{V}_E$, expressed in liters per minute ($l \cdot min^{-1}$), corresponds to the volume of air mobilized per minute, resulting from the product of the tidal volume (V_T) by the respiratory frequency (fr) (Holley et al. 2016). $\dot{V}_E$ must adapt at each level of exercise intensity to the needs of O_2 in muscles. $\dot{V}_E$ is also regulated to remove carbon dioxide (CO_2) from the blood to maintain normocapnia (Whipp and Pardy 1986). Any failure of this adaptation will result in physical performance limitations and discomfort during exercise (O'Donnell et al. 2009).

Numerous studies have shown that metabolic and anthropometric changes during puberty will have an influence on ventilatory response at maximal exercise ($\dot{V}_{Emax}$) in boys (Rutenfranz et al. 1981; Prioux et al. 1997; Burstein et al. 2020; Armstrong and Welsman 2020) and girls (Rutenfranz et al. 1981; Rowland and Cunningham 1997; Burstein et al. 2020; Armstrong and Welsman 2020). Several studies (Robinson 1938; Andersen et al. 1974; Rutenfranz et al. 1981; Boule et al. 1989; Armstrong et al. 1997; Rowland and Cunningham 1997; Ondrak and McMurray 2006; Marinov et al. 2007) have also analyzed the changes in ventilatory response at submaximal intensities during puberty. Nevertheless, only two of these studies are of longitudinal aspect (Rowland and Cunningham 1997; Rutenfranz et al. 1981) whereas the others are cross-sectional studies. However, the cross-sectional studies did not consider differences in physical maturation among subjects of the same chronological age (Matecki et al. 2003). Consequently, cross-sectional values give only the range of variability at a certain age and do not provide a true reference for the dynamic process of growth (Rutenfranz et al. 1981). Therefore, longitudinal studies can be expected to provide a clearer picture in changes of ventilatory response at submaximal exercise intensities compared to cross-sectional studies (Rowland and Cunningham 1997). Furthermore, among the two remaining longitudinal studies, Rowland and Cunningham, (1997) compared ventilatory responses according to age at absolute exercise intensities (walking speed: 3.25 mph) rather than relative exercise intensities. However, the absolute values did not consider the children's evolution of physical fitness with the age parameter. Indeed, the same intensity, expressed in absolute value, may result in greater ventilatory responses in younger and smaller subjects when compared to the older and larger participants (Ondrak and McMurray 2006). Finally, Rutenfranz

et al. (1981) have studied the ventilatory response during a maximal incremental step test performed on a cycle ergometer using relative intensities which varied between 50 and 70% of $\dot{V}O_{2max}$. However, the choice of these exercise intensities is never justified by the authors. To date, no longitudinal studies have analyzed the ventilatory response during exercise in children and adolescents at exercise intensities determined by ventilatory threshold (V_{Th}). Nevertheless, it is well known that ventilatory responses differ according to relative exercise intensity and particularly as a function of V_{Th} (Prado et al. 2010). Indeed, during the first minutes of a maximal incremental test, during which the power increases every minute, $\dot{V}_E$ increases proportionally to the metabolic rate determined by the oxygen uptake ($\dot{V}O_2$) and/or carbon dioxide output ($\dot{V}CO_2$) measurements. When exercise intensity exceeds an average of 50–60% of $\dot{V}O_{2max}$, which corresponds to the V_{Th} , the increase in $\dot{V}_E$ accelerates while $\dot{V}O_2$ continues to increase linearly with exercise intensity (Wasserman et al. 1967). A second non-linear increase in $\dot{V}_E$ is observed when the metabolic rate reaches approximately 80–90% of the subject's $\dot{V}O_{2max}$. At this point, $\dot{V}_E$ increases disproportionately to $\dot{V}O_2$ and $\dot{V}CO_2$ (Wasserman et al. 1986). Our semi-longitudinal study, covering a total age range of 11–17 years in boys and 11–15 years in girls, is, therefore, in line with that of Rutenfranz et al (1981). Its objective was thus to further specify the changes with maturation of submaximal ventilatory response during a maximal incremental step test. To do so, we compared the ventilatory responses according to age at three exercise intensities chosen according to V_{Th} measured during a maximal incremental step test, i.e., under V_{Th} corresponding to 30% of $\dot{V}O_{2max}$, around V_{Th} corresponding to 60% of $\dot{V}O_{2max}$ and above V_{Th} corresponding to 90% of $\dot{V}O_{2max}$.

Materials and methods

Subjects

Fifty-eight healthy untrained boys ($n=54$) and girls ($n=14$) started in this study. None of them had ever taken part in training or athletic competition. Time spent in extracurricular physical activities was between $2h49 \text{ min} \pm 0.32$ and $4h28 \text{ min} \pm 0.67$ per week for the boys (Table 1) and between $2h34 \text{ min} \pm 0.44$ and $4h18 \text{ min} \pm 1.18$ for the girls (Table 2). Annually, at the same period and for 3 years, the children performed a maximal incremental step test on a bicycle ergometer in their school. Five different age groups were established with an initial age for boys of 11.2 ± 0.50 years (group I— $n=22$), 12.9 ± 0.71 years (group II— $n=18$), and 14.9 ± 0.75 years (group III— $n=14$). Concerning girls, the initial age was of 11.2 ± 0.61 years (group IV— $n=7$), and 12.9 ± 1.11 years (group V— $n=7$). Concerning boys,

Table 1 Changes in physical activity practices and anthropometric characteristics in boys

Groups	I (n = 22)			II (n = 18)			III (n = 14)		
Age (years)	11.2 (0.50)	12.2 (0.48)	13.2 (0.83)	12.9 (0.71)	13.9 (0.93)	14.8 (0.89)	14.9 (0.75)	15.9 (0.82)	16.9 (0.77)
PA h:min	3.26 (0.40)	3.26 (0.44)	3.28 (0.47)	NS	NS	3.43 (0.37)	NS	3.42 (0.89)	4.28 (0.67)
Height (cm)	143.5 (1.05)	148.4 (1.19)	155.1 (1.28)*	NS	153.5 (1.79)	167.7 (1.59)*	NS	172.6 (2.12)	174.7 (1.88)*
BM (kg)	36.0 (0.99)	39.2 (1.20)	44.2 (1.57)*	NS	44.1 (1.65)	56.5 (1.65)*	NS	60.4 (2.12)	63.6 (1.83)*
LBM (kg)	31.5 (0.61)	34.0 (0.80)	38.7 (0.99)*	NS	38.4 (1.21)	50.1 (1.28)*	NS	53.6 (1.55)	55.2 (1.05)*

Values are means $\pm$ SEM

PA physical activity, BM total body mass, LBM lean body mass, NS no significant difference between groups I and II at 13 years and between groups II and III at 15 years

* $p < 0.05$ between third and first year in different groups

the children in group I were tested from 11.2 ± 0.50 to 13.2 ± 0.83 years, children in group II from 12.9 ± 0.71 to 14.8 ± 0.89 years and children in group III from 14.9 ± 0.75 to 16.9 ± 0.77 years. Concerning girls, the children in group IV were tested from 11.2 ± 0.61 to 13.0 ± 0.57 and children in group V from 12.9 ± 1.11 to 14.9 ± 1.72 . Subjects and their parents provided informed consent following an explanation of the study's procedures and objectives. The study protocol was approved by the hospital's ethics committee.

Measurements

Anthropometric measurements: the following measurements were performed: total body mass (BM), height and skinfold thickness (bicipital, tricipital, subscapular and supra-iliac). All measurements were taken by the same observer according to technique and positions established by the International Biological Program (Weiner and Lourie 1981). Body fat mass was assessed from four skinfold thickness measurements according to Durnin and Rahaman (1967). Lean body mass (LBM) was calculated by subtracting body fat mass from BM.

Stage of development: the same pediatrician assessed the level of pubertal maturation by analyzing pubic hair growth according to Tanner's five stages (Tanner 1962). The three age groups corresponded to three maturational groups: pre-pubertal, stage I (groups I and IV), pubertal, stages II and III (groups II and V) and post-pubertal, stages IV and V (group III). In this classification, stage 1 represents the immature, prepubertal state, while stage 5 represents fully matured adolescence.

Gas exchange measurements: a nose clip and a buccal piece were attached to subjects. During exercise, the subjects breathed through a low-resistance valve (Warren E. Collins, Inc., Mass., USA) attached to a large tubing (i.d. 3.5 cm) into a 5 L mixing chamber. Inspiratory airflow was measured with a Fleisch no. 3 pneumotachometer (Godard, Statham, Hollande) and a pressure transducer (MP 45, Vali-dyne, Engineering Corp., Calif., USA) with a measuring range of ± 2 cmH₂O. The pneumotachograph was placed on the inspiratory line to avoid problems linked to water vapor. Calibration of the flow module was accomplished by introducing a measured volume of air for several flows. Expired gases were sampled in the mixing box and analyzed for oxygen (O₂) with a polarographic analyzer (OM 11, Sensormedics Corp., Calif., USA). Carbon dioxide (CO₂) was analyzed with an infrared analyzer (Diamant 6000, Cosma, France). Gas analyzers were calibrated before and after each test with standard gases. Inspiratory flow and fractions of expired O₂ and CO₂ were treated by a computer that calculated the following parameters from 10 breathing cycles: $\dot{V}_E$, $\dot{V}_T$, fr, $\dot{V}$ O₂ and $\dot{V}$ CO₂.

Table 2 Changes in physical activity practices and anthropometric characteristics in girls

Groups	IV (n = 7)			V (n = 7)		
Age (years)	11.2 (0.61)	12.2 (0.81)	13.0 (0.57)	12.9 (1.11)	13.9 (1.11)	14.9 (1.72)
PA h:min	3.48 (1.10)	4.12 (1.06)	4.18 (1.18)	NS 3.30 (0.72)	2.34 (0.44)	3.0 (0.68)
Height (cm)	148.7 (2.44)	154.6 (2.25)	158.1 (2.09)*	NS 153.9 (3.21)	158.0 (2.89)	160.7 (2.54)*
BM (kg)	40.4 (2.14)	44.3 (1.63)	48.7 (1.66)*	S 40.5 (2.44)	44.6 (2.68)	47.7 (2.04)*
LBM (kg)	33.0 (1.64)	35.9 (1.42)	39.5 (1.39)*	S 33.4 (1.82)	35.9 (1.71)	38.0 (1.64)*

Values are means $\pm$ SEM

PA physical activity, BM total body mass, LBM lean body mass, NS no significant difference between groups IV and V at 13 years, S significant difference between groups IV and V at 13 years

* $p < 0.05$ between third and first year in different groups

Ventilatory threshold: to determine V_{Th} during the maximal incremental step test, we used the respiratory equivalent method (Wasserman et al. 1973) in which V_{Th} corresponds to the point at which the respiratory O_2 equivalent ($\dot{V}_E/\dot{V}O_2$) begins to increase while respiratory CO_2 equivalent ($\dot{V}_E/\dot{V}CO_2$) remains stable. Two observers determined V_{Th} visually and independently.

Protocol

All examinations, as well as tests, were carried out in the schools. Clinical examination and an electrocardiogram were carried out at the beginning of the testing procedure. During the clinical examination, the anthropometric measurements were taken. Each subject was then asked to perform a maximal incremental step test in a sitting position on a cycle ergometer (EPS 990, Bodyguard Jonas Oglund AS, Norway). The electrocardiogram was continuously monitored with a cardio scope (Diascope Simonsen and Weel, Denmark). A continuous progressive protocol was used: after 3 min of warm-up, exercise intensity was increased until exhaustion. For children from age 10.8 to 12 years, the exercise intensity was increased by steps of $20 \text{ W} \cdot \text{min}^{-1}$ and for the other children, by steps of $30 \text{ W} \cdot \text{min}^{-1}$. The children were instructed to maintain a constant pedaling rate of 50 rpm and were actively encouraged throughout the test. The ventilatory measurement was taken during the last 30 s of each exercise period. $\dot{V}O_{2max}$ was achieved when three of the following criteria were obtained: a steady heart rate (HR) at a value close to the theoretical maximal HR, a respiratory exchange ratio (R) greater than 1.1, a constant $\dot{V}O_2$ despite the increased exercise intensity and the impossibility for the subject to maintain a pedaling rate of 50 rpm. $\dot{V}_{Emax}$ was defined when $\dot{V}O_{2max}$ was achieved. HR was measured from five recorded ventricular complexes after each effort. All subjects performed the same testing protocol 12 and 24 months later.

Lung function: the measurements of the flow-volume loops and volume-time curve were performed on a digital spirometer (Datalink pulmochart). The maximum expiratory

flow (MEF) forced expiratory volume in 1 s (FEV_1), and vital capacity (VC) were measured on this occasion.

Statistical analysis

All values are given as means $\pm$ SEM. One-way analysis of variance was used to measure the annual effects, in all groups, of age on anthropometric characteristics and ventilatory parameters. Concerning boys, the measurements were performed from 11.2 ± 0.50 to 13.2 ± 0.83 years in group I, from 12.9 ± 0.71 to 14.8 ± 0.89 years in group II and from 14.9 ± 0.75 to 16.9 ± 0.77 years in group III. Concerning girls, the measurements were performed from 11.2 ± 0.61 to 13.0 ± 0.57 years in group IV and from 12.9 ± 1.11 to 14.9 ± 1.72 years in group V. Student's t test was used to compare the values of parameters between groups I and II (in boys) and IV and V (in girls) at 13 years and between groups II and III (in boys) at 15 years. To study the changes of ventilatory response with age at different percentages of $\dot{V}O_{2max}$ (30%, 60% and 90%), we determined the best regression equation that related each subject's ventilatory response to the percentage of $\dot{V}O_{2max}$. The relationships were exponential for $\dot{V}_E$ and fr and logarithmic for V_T . For each of these relationships, the correlation coefficients were high. We then calculated the values of the different ventilatory parameters for each percentage of $\dot{V}O_{2max}$. The changes of ventilatory response with age at different percentages of $\dot{V}O_{2max}$ were tested by one-way analysis of variance for repeated measurements completed by a Newman-Keuls test when the ANOVA F ratio was significant ($p < 0.05$). The analyses were carried out on all ventilatory parameters, whether expressed as absolute or relative values, and for all age groups. Values of $p < 0.05$ were considered significant throughout the study.

To compare the kinetics of the ventilatory variables as a function of age, sex and at the three different intensities, we used a two-way analysis of variance for repeated measurements completed by a Newman-Keuls test when the ANOVA F ratio was significant ($p < 0.05$). This analysis of variance was used only for groups I (from 11.2 ± 0.50 years to 13.2 ± 0.83 years)

and II (from 12.9 ± 0.71 years to 14.8 ± 0.89 years) in boys and IV (from 11.2 ± 0.61 to 13.0 ± 0.57 years) and V (from 12.9 ± 1.11 to 14.9 ± 1.72 years) in girls.

Results

Anthropometric characteristics and physical activity

Height, BM and LBM increased ($p < 0.05$) in groups I, II and III for boys (Table 1) and in groups IV and V for girls (Table 2). Concerning boys, no significant differences were observed between groups I and II at 13 years and between groups II and III at 15 years. Differences ($p < 0.05$) were observed in girls between groups IV and V at 13 years, regarding BM and LBM. The time spent in extracurricular physical activities does not change significantly regardless of the sex and age of the subjects (Tables 1 and 2).

Maximal oxygen uptake and ventilatory threshold

Concerning boys, $\dot{V}O_{2max}$ in $l \cdot min^{-1}$ increased ($p < 0.05$) in groups I and II and $\dot{V}O_{2max}$ in $ml \cdot min^{-1} \cdot kg^{-1}$ increased ($p < 0.05$) only in group I (Table 3). Concerning girls (Table 4), $\dot{V}O_{2max}$ in $l \cdot min^{-1}$ increased ($p < 0.05$) only in group IV and no significant difference was observed in any group regarding $\dot{V}O_{2max}$ in $ml \cdot min^{-1} \cdot kg^{-1}$. V_{Th} in $l \cdot min^{-1}$ increased ($p < 0.05$) in groups II and III for boys and in groups IV and V for girls. Concerning boys, differences ($p < 0.05$) were observed at 13 years between groups I and II regarding $\dot{V}O_{2max}$ in $ml \cdot min^{-1} \cdot kg^{-1}$ and at 15 years between groups II and III regarding V_{Th} in $\% \dot{V}O_{2max}$. Concerning girls, a difference ($p < 0.05$) was observed at 13 years between groups IV and V regarding V_{Th} in $l \cdot min^{-1}$.

Maximal ventilation and pulmonary function parameters

Concerning boys (Table 5), $\dot{V}_{Emax}$, FEV_1 and VC increased ($p < 0.05$) in groups I, II and III, and MEF increased only in group II. Concerning girls (Table 6), $\dot{V}_{Emax}$ increased ($p < 0.05$) in group IV, FEV_1 , and VC increased ($p < 0.05$) in groups IV and V and no significant change was observed regarding MEF. No significant difference was observed for any parameters at 13 years between groups I and II (in boys) and IV and V (in girls) and at 15 years between groups II and III (in boys).

Changes in ventilatory response according to age and exercise intensity

Expressed in absolute value. Concerning boys (Fig. 1), $\dot{V}_E$ increased ($p < 0.05$) in groups I and II at all three intensities. In group III, $\dot{V}_E$ also increased ($p < 0.05$) but only at 60% and

Table 3 Changes in maximal oxygen uptake ($l \cdot min^{-1}$, $ml \cdot min^{-1} \cdot kg^{-1}$), oxygen uptake ($\%$, $l \cdot min^{-1}$ et $ml \cdot min^{-1} \cdot kg^{-1}$) and heart rate (bpm) at ventilatory threshold in boys

Groups	I (n = 22)			II (n = 18)			III (n = 14)		
Age (years)	11.2 (0.50)	12.2 (0.48)	13.2 (0.83)	12.9 (0.71)	13.9 (0.93)	14.8 (0.89)	14.9 (0.75)	15.9 (0.82)	16.9 (0.77)
$\dot{V}O_{2max}$ ($l \cdot min^{-1}$)	1.62 (0.06)	1.77 (0.05)	2.14 (0.1)*	2.09 (0.09)	2.30 (0.11)	2.64 (0.09)*	2.73 (0.13)	2.88 (0.11)	3.04 (0.13)
$\dot{V}O_{2max}$ ($ml \cdot min^{-1} \cdot kg^{-1}$)	45.2 (1.81)	45.8 (1.45)	55.2 (1.77)*	47.9 (1.73)	46.8 (2.19)	47.1 (1.53)	47.6 (1.24)	47.9 (1.44)	47.9 (1.84)
V_{Th} ($\% \dot{V}O_{2max}$)	62.5 (2.67)	68.1 (2.56)	60.8 (2.03)	57.1 (2.57)	60.0 (2.4)	62.8 (2.16)	54.6 (2.13)	57.7 (2.12)	59.4 (2.81)
V_{Th} ($l \cdot min^{-1}$)	0.962 (0.05)	1.19 (0.04)	1.29 (0.07)	1.18 (0.06)	1.37 (0.05)	1.62 (0.08)*	1.49 (0.09)	1.67 (0.1)	1.80 (0.9)*
V_{Th} ($ml \cdot min^{-1} \cdot kg^{-1}$)	27.8 (1.65)	31.4 (1.38)	29.3 (1.33)	27.2 (1.36)	27.9 (0.95)	28.9 (1.5)	26.2 (1.17)	27.7 (1.37)	29.7 (1.42)
HR (bpm)	153.2 (3.38)	160.2 (3.55)	150.9 (3.28)	143.8 (4.04)	146.8 (3.54)	152.8 (3.51)	143.6 (3.11)	146.3 (3.21)	152.9 (5.55)

Values are means $\pm$ SEM

$\dot{V}O_{2max}$ maximal oxygen uptake, V_{Th} ventilatory threshold, HR heart rate, NS no significant difference between groups I and II at 13 years and between groups II and III at 15 years, S significant difference between groups I and II at 13 years and between groups II and III at 15 years

* $p < 0.05$ between third and first year in different groups

Table 4 Changes in maximal oxygen uptake ($\text{l}\cdot\text{min}^{-1}$, $\text{ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$), oxygen uptake (% $\text{l}\cdot\text{min}^{-1}$ et $\text{ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$) and heart rate (bpm) at ventilatory threshold in girls

Groups	IV ($n=7$)			V ($n=7$)			
Age (years)	11.2 (0.61)	12.2 (0.81)	13.0 (0.57)		12.9 (1.11)	13.9 (1.11)	14.9 (1.72)
$\dot{V}O_{2\text{max}}$ ($\text{l}\cdot\text{min}^{-1}$)	1.51 (0.08)	1.73 (0.10)	1.89 (0.04)*	NS	1.72 (0.10)	1.83 (0.13)	1.87 (0.08)
$\dot{V}O_{2\text{max}}$ ($\text{ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$)	37.9 (2.42)	39.3 (2.47)	39.0 (1.63)	NS	43.1 (2.69)	41.5 (2.81)	39.5 (2.34)
V_{Th} (% $\dot{V}O_{2\text{max}}$)	69.9 (3.57)	55.1 (2.42)	65.8 (2.86)	NS	56.6 (4.75)	52.6 (3.31)	62.6 (3.61)
V_{Th} ($\text{l}\cdot\text{min}^{-1}$)	1.03 (0.06)	0.96 (0.09)	1.25 (0.05)*	S	0.95 (0.04)	0.96 (0.05)	1.17 (0.09)*
V_{Th} ($\text{ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$)	25.6 (0.69)	21.8 (1.94)	26.2 (2.14)	NS	24.1 (2.17)	21.8 (1.95)	25.0 (2.51)
HR (bpm)	153.9 (3.76)	141.6 (6.91)	154.8 (7.95)	NS	150.3 (6.75)	139.2 (4.32)	161.1 (5.73)

Values are means $\pm$ SEM

$\dot{V}O_{2\text{max}}$ maximal oxygen uptake, V_{Th} ventilatory threshold, HR heart rate, NS no significant difference between groups IV and V at 13 years, S significant difference between groups between groups IV and V at 13 years

* $p < 0.05$ between third and first year in different groups

90% $\dot{V}O_{2\text{max}}$. For V_{T} , increases ($p < 0.05$) were observed in all three groups and at all three intensities. Finally, no significant change was observed for fr in all three groups and at all three intensities and no significant differences were observed between groups I and II at 13 years and between groups II and III at 15 years for any of the ventilatory parameters. Concerning girls (Fig. 2), $\dot{V}_E$ increased ($p < 0.05$) in group IV at all three intensities and no significant increase was observed in group V. For V_{T} , increases ($p < 0.05$) were observed in group IV at all three intensities. In group V, V_{T} also increases ($p < 0.05$) but only at 60% and 90% $\dot{V}O_{2\text{max}}$. Finally, fr tended to stabilize in both groups at all three intensities, with no significant change observed. For V_{T} , differences ($p < 0.05$) were observed between groups IV and V at 13 years.

Expressed in relative value. Concerning boys, no significant changes were observed for $\dot{V}_E\cdot\text{kg}^{-1}$, which tends to stabilize in all three groups and at all three intensities (Fig. 3). $V_{\text{T}}\cdot\text{kg}^{-1}$ increased ($p < 0.05$) in group I at 60% and 90% $\dot{V}O_{2\text{max}}$ and in group II but only at 90% $\dot{V}O_{2\text{max}}$. No other significant changes in $V_{\text{T}}\cdot\text{kg}^{-1}$ were observed in group III and no significant differences between groups I and II at 13 years and between groups II and III at 15 years were observed for any of the ventilatory parameters. Concerning girls, except for a significant difference of $\dot{V}_E\cdot\text{kg}^{-1}$ and $V_{\text{T}}\cdot\text{kg}^{-1}$ in group IV at 30% $\dot{V}O_{2\text{max}}$ between 12 and 13 years, these parameters tend to stabilize in groups IV and V (Fig. 4). A difference ($p < 0.05$) was observed between groups IV and V at 13 years for $\dot{V}_E\cdot\text{kg}^{-1}$ at 30% $\dot{V}O_{2\text{max}}$. No other significant difference was observed at 13 years between groups IV and V.

Changes in ventilatory response according to age, exercise intensity and sex

Expressed in absolute values. Figure 5 shows that $\dot{V}_E$ in boys was significantly higher than that of girls from 11 to

13 years and from 13 to 15 years at either 30% ($p < 0.01$), 60% ($p < 0.01$) or 90% $\dot{V}O_{2\text{max}}$ ($p < 0.05$). No other significant differences were observed for V_{T} and fr.

Expressed in relative values. No significant difference was observed for $V_{\text{T}}\cdot\text{kg}^{-1}$ (Fig. 6). In contrast, $\dot{V}_E\cdot\text{kg}^{-1}$ was significantly higher ($p < 0.05$) between 11 and 13 years in boys compared to girls at 30%, 60% and 90% $\dot{V}O_{2\text{max}}$. No significant difference between boys and girls was observed between 13 and 15 years.

Important note: for the sake of clarity, some results of the study were included in the “supplementary material” section placed at the end of the manuscript. This supplementary data comprise the changes in ventilation according to carbon dioxide output and the changes in respiratory carbon dioxide equivalent according to oxygen uptake.

Discussion

The aim of this semi-longitudinal study was to specify in boys and girls the changes, during growth, of submaximal ventilatory response during a maximal incremental test. Our results show significant changes in ventilatory response with age and sex, whether expressed in absolute or relative values.

The effects of age and sex on ventilatory response

Robinson (1938) showed that $\dot{V}_E$ increased from 6 to 17 years during a standardized treadmill walk test at constant intensity. The results of Rutenfranz et al. (1981) corroborated those of Robinson (1938). They found that $\dot{V}_E$ increased from 12 to 15 years and then stabilized until 17 years. While our results, up to 15 years, agree with those of Rutenfranz et al. (1981), they showed that $\dot{V}_E$ increased significantly up to age 17 at the highest exercise intensities (Fig. 1). These results agree with the results of our previous

Table 5 Changes in maximal ventilation and pulmonary function parameters in boys

Groups	I (n = 22)			II (n = 18)			III (n = 14)		
Age (Years)	11.2 (0.50)	12.2 (0.48)	13.2 (0.83)	12.9 (0.71)	13.9 (0.93)	14.8 (0.89)	14.9 (0.75)	15.9 (0.82)	16.9 (0.77)
$\dot{V}_{E\max}$ (l.min ⁻¹)	57.70 (1.87)	62.84 (1.84)	74.55 (2.57)*	NS	76.44 (2.72)	90.35 (2.96)*	NS	94.90 (4.35)	115.0 (4.92)*
MEF (l.s ⁻¹)	2.47 (0.10)	2.43 (0.12)	2.80 (0.20)	NS	3.02 (0.15)	3.66 (0.16)*	NS	3.90 (0.28)	4.16 (0.24)
FEV ₁ (l)	2.04 (0.05)	2.08 (0.05)	2.46 (0.08)*	NS	2.79 (0.12)	3.30 (0.12)*	NS	3.68 (0.18)	3.83 (0.11)*
VC (l)	2.40 (0.05)	2.49 (0.06)	2.89 (0.08)*	NS	3.46 (0.17)	4.01 (0.19)*	NS	4.46 (0.18)	4.65 (0.14)*

Values are means $\pm$ SEM

$\dot{V}_{E\max}$ maximal expiratory flow, MEF maximum expiratory flow, FEV₁ forced expiratory volume (1 s), VC vital capacity, NS no significant difference between groups I and II at 13 years and between groups II and III at 15 years

* $p < 0.05$ between third and first year in different groups

study (Prioux et al. 1997) and those of this study (Table 5), which showed that $\dot{V}_{E\max}$ increased significantly between 15 and 17 years (Table 5). However, the $\dot{V}_E$ values observed by Rutenfranz et al. (1981) at 12, 15 and 17 years seem higher than those of our study at 60% of $\dot{V}O_{2\max}$. These differences can probably be explained by the methodologies used. Indeed, Rutenfranz et al. (1981) measured $\dot{V}_E$ at the same exercise intensity (between 50 and 70% of $\dot{V}O_{2\max}$) whereas we evaluated $\dot{V}_E$, V_T and fr at three different intensities (below 30% of $\dot{V}O_{2\max}$, around 60% of $\dot{V}O_{2\max}$ and above 90% of $\dot{V}O_{2\max}$). Regardless of the methodological differences discussed previously, the slightly higher exercise intensity in the study by Rutenfranz et al. (1981) compared to ours could also explain the differences of $\dot{V}_E$ between our studies. Indeed, at these exercise intensities, the increase in $\dot{V}_E$ is exponential: a small increase in intensity leads to a proportionally larger increase in $\dot{V}_E$ (Wasserman et al. 1973). Rutenfranz et al. (1981), in their study, were also interested in changes in $\dot{V}_E$, as a function of age, in girls. These changes appear to be different than for boys. Indeed, their results showed that $\dot{V}_E$ did not increase for exercise intensities between 65 and 70% of $\dot{V}O_{2\max}$, and that it remained stable between 12 and 17 years. Similar results were observed by these authors for lower exercise intensities, i.e., between 50 and 65% of $\dot{V}O_{2\max}$. Our results were not fully in agreement with those of Rutenfranz et al. (1981). They showed no significant increase in $\dot{V}_E$ between 13 and 15 years, regardless of exercise intensity, with a significant increase in $\dot{V}_E$ between 11 and 13 years (Fig. 2). However, these results agree with those observed in $\dot{V}_{E\max}$ (Table 6). Indeed, they showed that $\dot{V}_{E\max}$ increased significantly between 11 and 13 years without any change between 13 and 15 years. Given the relationship between BM, LBM and $\dot{V}_{E\max}$ (Mercier et al. 1991; Armstrong and Welsman 2020) it is likely that $\dot{V}_{E\max}$ did not increase significantly between 13 and 15 years because BM and LBM also did not increase during this period. Finally, regarding the differences in ventilatory response between boys and girls, our results agree with those of Rutenfranz et al. (1981) which showed, from the age of 12 years, a significantly higher $\dot{V}_E$ in boys than girls for the same percentage of $\dot{V}O_{2\max}$. Our results also seem to agree with those of Armstrong et al. (1997). The results of this study showed that $\dot{V}_E$ was significantly higher in boys than in girls, either between 70 and 75% of $\dot{V}O_{2\max}$ or between 80 and 85% of $\dot{V}O_{2\max}$.

Similar to $\dot{V}_E$, few studies have analyzed the changes in V_T and fr during submaximal intensity exercise. First, while no significant differences were observed between groups I and II at 13 years and between groups II and III at 15 years in boys, significant differences in V_T were observed at 13 years between groups IV and V in girls (Fig. 2). Indeed, regardless of exercise intensity, V_T at 13 years in group IV was always higher than V_T in group

Table 6 Changes in maximal ventilation and pulmonary function variables in girls

Groups	IV (<i>n</i> = 7)				V (<i>n</i> = 7)		
Age (years)	11.2 (0.61)	12.2 (0.81)	13.0 (0.57)		12.9 (1.11)	13.9 (1.11)	14.9 (1.72)
$\dot{V}_{E_{max}}$ (l.min ⁻¹)	50.42 (3.52)	59.16 (4.12)	72.25 (5.51)*	NS	62.88 (4.47)	70.35 (3.15)	74.79 (4.66)
MEF (l.s ⁻¹)	2.89 (0.22)	2.89 (0.22)	3.28 (0.18)	NS	3.38 (0.61)	3.06 (0.33)	3.48 (0.15)
FEV ₁ (l)	2.35 (0.13)	2.39 (0.15)	2.66 (0.10)*	NS	2.60 (0.18)	2.67 (0.17)	2.95 (0.14)*
VC (L)	2.57 (0.13)	2.77 (0.20)	3.04 (0.10)*	NS	2.87 (0.18)	3.14 (0.15)	3.48 (0.21)*

Values are means $\pm$ SEM

$\dot{V}_{E_{max}}$ maximal ventilation, *MEF* maximum expiratory flow, *FEV₁* forced expiratory volume (1 s), *VC* vital capacity, *NS* no significant difference between groups IV and V at 13 years

**p* < 0.05 between third and first year in different groups

V. These differences seem to be directly related to anthropometric characteristics. Indeed, BM and LBM are the anthropometric characteristics that best explain the changes in $\dot{V}_{E_{max}}$ and $V_{T_{max}}$ during growth (Mercier et al. 1991; Armstrong and Welsman 2020) and BM and LBM were significantly higher among 13-year-old girls in group IV (Table 2). However, when V_T was expressed relatively to BM (Fig. 4) the significant differences disappeared. The significant differences in BM and LBM at 13 years between groups IV and V can probably be explained by the small number of subjects (*n* = 7) in each group of girls and by heterogeneity in pubertal maturation levels between girls in groups IV and V.

Second, the significant increase in $\dot{V}_E$, up to 17 years in boys, was due to a significant increase in VC, and therefore, V_T (Prioux et al. 1997), while *fr* tended to decrease (Fig. 1) but without significant change. Robinson's (1938) results showed that V_T was 430 ml in the youngest children (6 years) and 1.73 l in the oldest (17 years). The study by Andersen et al. (1974) corroborated these results. They showed, for a relative intensity between 50 and 60% of $\dot{V}_{O_{2max}}$, an increase in V_T from 530 ± 100 to 1760 ± 740 ml in boys and from 460 ± 120 to 810 ± 100 ml in girls. Our study's results appear to be consistent with those outlined above. Indeed, a significant increase was observed in V_T from 11 to 13 years, 13–15 years, and 15–17 years, regardless of exercise intensity. In girls, V_T also increased significantly from 11 to 13 years and 13–15 years in group V except for V_T between 13 and 15 years at 30% $\dot{V}_{O_{2max}}$ (Fig. 2). The fact that the increase in V_T can be explained by the increase in VC, as indicated above, agrees with (i) the significant increase in FEV₁ and VC in boys (Table 5) and girls (Table 6), (ii) the linear relationships between FEV₁, VC and $V_{T_{max}}$ during growth (Rutenfranz et al. 1981), (iii) the fact that only half of the lung volume capacity is considered during maximal exercise (Rutenfranz et al. 1981) and most importantly (iv) the significant increase in $V_{T_{max}}$ and VC up to 17 years, which justifies the stability of the $V_{T_{max}}$ /VC ratio between 11 and 17 years (Prioux et al. 1997).

Third, the few studies focusing on *fr* during growth have shown a decrease in *fr* when age increased. Robinson (1938) observed that *fr* decreased in boys aged 6–17 years. Data from Andersen et al (1974) were similar to those of Rutenfranz et al. (1981) and confirmed those of Robinson (1938). Rutenfranz et al. (1981) have shown that an exercise carried out at an intensity between 65 and 70% of $\dot{V}_{O_{2max}}$ in children aged 12–17 years induced a decrease in *fr* from 39 to 28 breaths.min⁻¹ in boys and from 38 to 26 breaths.min⁻¹ in girls. These *fr* values were very close to those we observed at 60% of $\dot{V}_{O_{2max}}$ especially in boys (Fig. 1). Andersen et al. (1974) showed a decrease in *fr*, relatively to age, when children aged 8–16 years exercised on a bicycle ergometer at 50–60% of $\dot{V}_{O_{2max}}$ intensity or 70–80% of $\dot{V}_{O_{2max}}$ intensity. Rowland and Cunningham (1997) showed that *fr* decreased from 45 to 36 breaths.min⁻¹ in children aged 9–13 years. Finally, Ondrak and McMurray (2006) found that *fr* decreased with age regardless of exercise intensity. The results we observed in boys (Fig. 1) were consistent with those in the literature. Indeed, although not significant, *fr* tended to decrease in all age groups and for each intensity. A full longitudinal study conducted from 11 to 17 years of age could have shown a significant decrease for this parameter. The results observed in girls are more difficult to interpret. Indeed, Fig. 2 seems to indicate a tendency of *fr* to stabilize during growth. However, the comparison of *fr* kinetics as a function of sex (Fig. 5) showed no significant difference between girls and boys, which was consistent with the literature (Robinson 1938; Andersen et al. 1974; Rutenfranz et al. 1981). The trend of *fr*, with advancing age, would, therefore, be to decrease for both girls and boys.

The effects of age, sex, and body weight on ventilatory response

Height is the simplest parameter to measure when evaluating growth. It was, therefore, naturally proposed as a determining factor in the ventilatory response (Mercier et al. 1991; Rutenfranz et al. 1981; Rowland 1996). However,

Fig. 1 Changes in ventilatory response, expressed in absolute values, as a function of exercise intensity in boys. $\dot{V}_E$ ventilation, fr respiratory frequency, V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in % $\dot{V}O_{2max}$; values are means $\pm$ SEM; * $p < 0.05$; NS no significant difference between groups I and II at 13 years and between groups II and III at 15 years

Fig. 2 Changes in ventilatory response, expressed in absolute values, as a function of exercise intensity in girls. $\dot{V}_E$ ventilation, fr respiratory frequency, V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in % $\dot{V}O_{2max}$; values are means $\pm$ SEM; * $p < 0.05$; NS no significant difference between groups IV and V at 13 years

the systematic use of height as a determinant of V_{Emax} , recommended by Rowland, (1996), is relativized by the study of Mercier et al., (1991). Indeed, for these authors, BM and LBM are the anthropometric characteristics that best explain the variations in V_{Emax} and V_{Tmax} with

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Fig. 3 Changes in ventilatory response, expressed in relative values, as a function of exercise intensity in boys. $\dot{V}_E$ ventilation, V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in % $\dot{V}O_{2max}$; values are means $\pm$ SEM; * p < 0.05; NS no significant difference between groups I and II at 13 years and between groups II and III at 15 years

Fig. 4 Changes in ventilatory response, expressed in relative values, as a function exercise intensity in girls. $\dot{V}_E$ ventilation, V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in % $\dot{V}O_{2max}$; values are means $\pm$ SEM; * p < 0.05; NS no significant difference between groups IV and V at 13 years

growth. Thus, studies such as ours, which propose $\dot{V}_{Emax}$ and V_{Tmax} values only corrected by BM are not far from reality (Armstrong and Welsman 2020). Likewise, the use of BM also makes it possible to compare our values with those in the literature. Robinson (1938) found a decrease in $\dot{V}_E$.kg⁻¹ for boys aged 6–17 years. Similar results have been observed by Rowland and Cunningham (1997) who indicated that $\dot{V}_E$.kg⁻¹ decreased with age without any difference between boys and girls. More recently, Ondrak and McMurray (2006) found that $\dot{V}_E$.kg⁻¹ decreased with age, regardless of exercise intensity, in children 8–18 years. Our results do not coincide with those of the two previous studies. Indeed, $\dot{V}_E$.kg⁻¹ remained stable during growth

in boys (Fig. 3) and girls (Fig. 4) with significantly higher values in boys between 11 and 13 years, regardless of exercise intensity (Fig. 6). However, the comparison of our results with previous studies is questionable. Firstly, in the studies of Robinson et al. (1938) and Ondrak and McMurray, (2006) the exercise intensities are expressed in absolute values. Hence, each workload may have elicited greater ventilatory responses in the younger and smaller participants, compared to the older and larger participants. Secondly, Rowland and Cunningham (1997) focused on a small number of children (11 boys and 9 girls) and a relatively small age range (9–13 years). Thus, the variability in exercise protocols, the use of different submaximal intensities, the lack of evaluation of the subjects' body composition and level of physical activity may contribute to the variability of the results between the different studies. The $\dot{V}_E$.kg⁻¹ values proposed in our study can only be used as a guideline when interpreting exercise testing

Fig. 5 Changes in ventilatory response, expressed in absolute values, as a function of exercise intensity and sex. $\dot{V}_E$ ventilation, f_r respiratory frequency; V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in % $\dot{V}O_{2max}$; $\dot{V}O_{2max}$: maximum oxygen uptake; values are means $\pm$ SEM; NS no significant difference between groups boys and girls

Fig. 6 Changes in ventilatory response, expressed in relative values, as a function of exercise intensity and sex. $\dot{V}_E$ ventilation, V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in % $\dot{V}O_{2max}$; $\dot{V}O_{2max}$: maximum oxygen uptake; values are means $\pm$ SEM; NS no significant difference between groups boys and girls

in children. More complete analyses should be carried out on the changes of ventilatory response at submaximal intensities according to, for example, mechanical power developed relative to the child's total mass.

Concerning V_T .kg⁻¹, Robinson (1938) found a small increase when comparing to age: V_T .kg⁻¹ increased from 0.021 l.min⁻¹.kg⁻¹ at 6 years to 0.025 l.min⁻¹.kg⁻¹ at 17 years. More recently, Ondrak and McMurray (2006)

showed that $V_T \cdot \text{kg}^{-1}$ decreased with age, regardless of exercise intensity, in children aged 8–18 years. These results are not in agreement with those of Rowland and Cunningham (1997). Indeed, these authors found no significant changes for $V_T \cdot \text{kg}^{-1}$ in boys aged 9–13 years. Our results in boys showed a significant increase in $V_T \cdot \text{kg}^{-1}$ from 11 to 13 years at 60% and 90% of $\dot{V}O_{2\text{max}}$ and from 13 to 15 years at 90% of $\dot{V}O_{2\text{max}}$ (Fig. 3). From 15 years of age in group III and up to the age of 17 years, $V_T \cdot \text{kg}^{-1}$ no longer increased. These results suggest that, up to 15 years, the increase in V_T is greater than the increase in BM at high intensities (60% and 90% of $\dot{V}O_{2\text{max}}$). BM may, therefore, not be the best anthropometric parameter to consider when studying the changes of V_T during growth. The use of LBM appears to be more appropriate (Mercier et al. 1991; Armstrong and Welsman 2020). However, these results also assume that parameters, other than anthropometric characteristics, can influence the changes of $V_T \cdot \text{kg}^{-1}$ during growth. This does not seem to be the case for girls. Indeed, except for a significant increase in $V_T \cdot \text{kg}^{-1}$ between 12 and 13 years at 30% of $\dot{V}O_{2\text{max}}$, our results showed a remarkable stability of this parameter during growth (Fig. 4). Finally, the evolution of $V_T \cdot \text{kg}^{-1}$ during growth appears to be independent of sex, since no difference in $V_T \cdot \text{kg}^{-1}$ was observed between boys and girls (Fig. 6).

Strengths and limitations

Although breathing pattern data are presented in our study and helps to explain the changes in ventilation during growth, we have not fully considered how ventilatory control may change with age. It would be interesting (i) to add an index of operating lung volume (i.e., expiratory and inspiratory reserve volume) and (ii) to report $P_a\text{CO}_2$ or more practically $P_{\text{ET}}\text{CO}_2$ data. Indeed, these data would provide further detail regarding exercise ventilatory mechanics (i.e., presence of dynamic hyperinflation) and ventilatory control (i.e., estimates of dead space and alveolar ventilation). In addition, we should have used a more appropriate experimental model, such as a real longitudinal study from 11 to 15 years in girls and from 11 to 17 years in boys, to analyze changes in ventilatory responses at submaximal exercise intensities during the growth spurt period (Armstrong and Welsman 2020). Finally, the sample size differs substantially between boys and girls. Indeed, we have 54 healthy untrained boys against only 14 healthy untrained girls. Moreover, we have collected data from 11 to 17 years in boys and only from 11 to 15 years in girls. Despite the validity of our statistical analyses, it would be interesting to conduct other studies with more subjects of both sexes and over a longer period, especially for girls, so that (i) the data can reflect the general pediatric population in France and (ii) to use these data as age-specific normative values for exercise performance.

Conclusion

At submaximal intensities, $\dot{V}_E$, expressed in absolute values, increases between 11 and 17 years in boys and only between 11 and 13 years in girls. Increases in VC, and therefore, in V_T , is the main reason for $\dot{V}_E$ increases during growth. $\dot{V}_E$ in boys is higher than $\dot{V}_E$ in girls regardless of age and exercise intensity. $\dot{V}_E \cdot \text{kg}^{-1}$ is stable in boys and girls whatever the intensity of exercise with significantly lower values in girls compared to boys between 11 and 13 years, regardless of exercise intensity. In boys, $V_T \cdot \text{kg}^{-1}$ increases significantly from 11 to 15 years and then stabilizes until the age of 17 years while $V_T \cdot \text{kg}^{-1}$ tends to stabilize during growth in girls with no significant difference of $V_T \cdot \text{kg}^{-1}$ between boys and girls regardless of age and exercise intensity.

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