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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

22  
23

## Abbreviations

BM	Total body mass	
CO <sub>2</sub>	Carbon dioxide	24
fr	Respiratory frequency	25
fr <sub>max</sub>	Maximal respiratory frequency	26
HR	Heart rate	27
O <sub>2</sub>	Oxygen	28
R	Respiratory exchange ratio	29
T <sub>E</sub>	Expiratory time	30
T <sub>E</sub> max	Maximal expiratory time	31
T <sub>I</sub>	Inspiratory time	32
T <sub>I</sub> max	Maximal inspiratory time	33
T <sub>TOT</sub>	Total respiratory time	34
T <sub>TOT</sub>	Maximal total respiratory time	35
T <sub>TOT</sub> max	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 <sub>T</sub>	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).

**AQ3** Numerous studies have shown that metabolic and anthropometric changes during puberty will have an influence on ventilatory response at maximal exercise ( $\dot{V}_{E_{max}}$ ) 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  $11.2 \pm 0.50$  years (group I— $n=22$ ),  $12.9 \pm 0.71$  years (group II— $n=18$ ), and  $14.9 \pm 0.75$  years (group III— $n=14$ ). Concerning girls, the initial age was of  $11.2 \pm 0.61$  years (group IV— $n=7$ ), and  $12.9 \pm 1.11$  years (group V— $n=7$ ). Concerning boys,

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

Groups	I ( <i>n</i> = 22)			II ( <i>n</i> = 18)			III ( <i>n</i> = 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)
PA h:min	3.26 (0.40)	3.26 (0.44)	3.28 (0.47)	NS	3.50 (0.69)	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	160.8 (1.88)	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	49.7 (1.72)	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	43.7 (1.35)	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  $\pm$  0.50 to 13.2  $\pm$  0.83 years, children in group II from 12.9  $\pm$  0.71 to 14.8  $\pm$  0.89 years and children in group III from 14.9  $\pm$  0.75 to 16.9  $\pm$  0.77 years. Concerning girls, the children in group IV were tested from 11.2  $\pm$  0.61 to 13.0  $\pm$  0.57 and children in group V from 12.9  $\pm$  1.11 to 14.9  $\pm$  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  $\pm$  2 cmH<sub>2</sub>O. 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 (O<sub>2</sub>) with a polarographic analyzer (OM 11, Sensormedics Corp., Calif., USA). Carbon dioxide (CO<sub>2</sub>) 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 O<sub>2</sub> and CO<sub>2</sub> were treated by a computer that calculated the following parameters from 10 breathing cycles:  $\dot{V}_E$ ,  $V_T$ , fr,  $\dot{V}_{O_2}$  and  $\dot{V}_{CO_2}$ .

**Table 2** Changes in physical activity practices and anthropometric characteristics 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)
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

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

## 200 Protocol

201 All examinations, as well as tests, were carried out in the  
 202 schools. Clinical examination and an electrocardiogram  
 203 were carried out at the beginning of the testing procedure.  
 204 During the clinical examination, the anthropometric meas-  
 205 urements were taken. Each subject was then asked to per-  
 206 form a maximal incremental step test in a sitting position on  
 207 a cycle ergometer (EPS 990, Bodyguard Jonas Oglund AS,  
 208 Norway). The electrocardiogram was continuously moni-  
 209 tored with a cardio scope (Diascope Simonsen and Weel,  
 210 Denmark). A continuous progressive protocol was used:  
 211 after 3 min of warm-up, exercise intensity was increased  
 212 until exhaustion. For children from age 10.8 to 12 years,  
 213 the exercise intensity was increased by steps of  $20 \text{ W}\cdot\text{min}^{-1}$   
 214 and for the other children, by steps of  $30 \text{ W}\cdot\text{min}^{-1}$ . The chil-  
 215 dren were instructed to maintain a constant pedaling rate of  
 216 50 rpm and were actively encouraged throughout the test.  
 217 The ventilatory measurement was taken during the last 30 s  
 218 of each exercise period.  $\dot{V}O_{2max}$  was achieved when three  
 219 of the following criteria were obtained: a steady heart rate  
 220 (HR) at a value close to the theoretical maximal HR, a res-  
 221 piratory exchange ratio (R) greater than 1.1, a constant  $\dot{V}O_2$   
 222 despite the increased exercise intensity and the impossibility  
 223 for the subject to maintain a pedaling rate of 50 rpm.  $\dot{V}_{Emax}$   
 224 was defined when  $\dot{V}O_{2max}$  was achieved. HR was measured  
 225 from five recorded ventricular complexes after each effort.  
 226 All subjects performed the same testing protocol 12 and  
 227 24 months later.

228 Lung function: the measurements of the flow-volume  
 229 loops and volume-time curve were performed on a digital  
 230 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

234 All values are given as means  $\pm$  SEM. One-way analysis  
 235 of variance was used to measure the annual effects, in all  
 236 groups, of age on anthropometric characteristics and ventila-  
 237 tory parameters. Concerning boys, the measurements were  
 238 performed from  $11.2 \pm 0.50$  to  $13.2 \pm 0.83$  years in group I,  
 239 from  $12.9 \pm 0.71$  to  $14.8 \pm 0.89$  years in group II and from  
 240  $14.9 \pm 0.75$  to  $16.9 \pm 0.77$  years in group III. Concerning  
 241 girls, the measurements were performed from  $11.2 \pm 0.61$   
 242 to  $13.0 \pm 0.57$  years in group IV and from  $12.9 \pm 1.11$  to  
 243  $14.9 \pm 1.72$  years in group V. Student's *t* test was used to  
 244 compare the values of parameters between groups I and II  
 245 (in boys) and IV and V (in girls) at 13 years and between  
 246 groups II and III (in boys) at 15 years. To study the changes  
 247 of ventilatory response with age at different percentages of  
 248  $\dot{V}O_{2max}$  (30%, 60% and 90%), we determined the best regres-  
 249 sion equation that related each subject's ventilatory response  
 250 to the percentage of  $\dot{V}O_{2max}$ . The relationships were expo-  
 251 nential for  $\dot{V}_E$  and fr and logarithmic for  $V_T$ . For each of  
 252 these relationships, the correlation coefficients were high.  
 253 We then calculated the values of the different ventilatory  
 254 parameters for each percentage of  $\dot{V}O_{2max}$ . The changes of  
 255 ventilatory response with age at different percentages of  
 256  $\dot{V}O_{2max}$  were tested by one-way analysis of variance for  
 257 repeated measurements completed by a Newman-Keuls  
 258 test when the ANOVA F ratio was significant ( $p < 0.05$ ).  
 259 The analyses were carried out on all ventilatory parameters,  
 260 whether expressed as absolute or relative values, and for all  
 261 age groups. Values of  $p < 0.05$  were considered significant  
 262 throughout the study.

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

269 and II (from  $12.9 \pm 0.71$  years to  $14.8 \pm 0.89$  years) in boys  
 270 and IV (from  $11.2 \pm 0.61$  to  $13.0 \pm 0.57$  years) and V (from  
 271  $12.9 \pm 1.11$  to  $14.9 \pm 1.72$  years) in girls.

## 272 Results

### 273 Anthropometric characteristics and physical activity

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

### 283 Maximal oxygen uptake and ventilatory threshold

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

### 297 Maximal ventilation and pulmonary function 298 parameters

299 Concerning boys (Table 5),  $\dot{V}_{E_{max}}$ , FEV<sub>1</sub> and VC increased  
 300 ( $p < 0.05$ ) in groups I, II and III, and MEF increased only  
 301 in group II. Concerning girls (Table 6),  $\dot{V}_{E_{max}}$  increased  
 302 ( $p < 0.05$ ) in group IV, FEV<sub>1</sub>, and VC increased ( $p < 0.05$ )  
 303 in groups IV and V and no significant change was observed  
 304 regarding MEF. No significant difference was observed for  
 305 any parameters at 13 years between groups I and II (in boys)  
 306 and IV and V (in girls) and at 15 years between groups II  
 307 and III (in boys).

### 308 Changes in ventilatory response according to age 309 and exercise intensity

310 Expressed in absolute value. Concerning boys (Fig. 1),  $\dot{V}_E$   
 311 increased ( $p < 0.05$ ) in groups I and II at all three intensities.  
 312 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)			
	Mean	SEM	Significance	Mean	SEM	Significance	Mean	SEM	Significance	
Age (years)	11.2 (0.50)	12.2 (0.48)		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)		2.09 (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)		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)		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)		1.18 (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)		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)		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)
$\dot{V}O_{2\max}$ ( $\text{l}\cdot\text{min}^{-1}$ )	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)
$\dot{V}O_{2\max}$ ( $\text{ml}\cdot\text{min}^{-1}\cdot\text{kg}^{-1}$ )	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)
$V_{Th}$ (% $\dot{V}O_{2\max}$ )	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

$\dot{V}O_{2\max}$  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

313 90% $\dot{V}O_{2\max}$ . For  $V_{T\cdot}$  increases ( $p < 0.05$ ) were observed in all  
 314 three groups and at all three intensities. Finally, no signifi-  
 315 cant change was observed for fr in all three groups and at all  
 316 three intensities and no significant differences were observed  
 317 between groups I and II at 13 years and between groups II  
 318 and III at 15 years for any of the ventilatory parameters. Con-  
 319 cerning girls (Fig. 2),  $\dot{V}_E$  increased ( $p < 0.05$ ) in group IV at  
 320 all three intensities and no significant increase was observed  
 321 in group V. For  $V_{T\cdot}$  increases ( $p < 0.05$ ) were observed in  
 322 group IV at all three intensities. In group V,  $V_{T\cdot}$  also increases  
 323 ( $p < 0.05$ ) but only at 60% and 90% $\dot{V}O_{2\max}$ . Finally, fr tended  
 324 to stabilize in both groups at all three intensities, with no sig-  
 325 nificant change observed. For  $V_{T\cdot}$  differences ( $p < 0.05$ ) were  
 326 observed between groups IV and V at 13 years.

327 Expressed in relative value. Concerning boys, no significant  
 328 changes were observed for  $\dot{V}_E\cdot\text{kg}^{-1}$ , which tends to stabilize  
 329 in all three groups and at all three intensities (Fig. 3).  $V_{T\cdot}\text{kg}^{-1}$   
 330 increased ( $p < 0.05$ ) in group I at 60% and 90% $\dot{V}O_{2\max}$  and in  
 331 group II but only at 90% $\dot{V}O_{2\max}$ . No other significant changes  
 332 in  $V_{T\cdot}\text{kg}^{-1}$  were observed in group III and no significant differ-  
 333 ences between groups I and II at 13 years and between groups  
 334 II and III at 15 years were observed for any of the ventila-  
 335 tory parameters. Concerning girls, except for a significant dif-  
 336 ference of  $\dot{V}_E\cdot\text{kg}^{-1}$  and  $V_{T\cdot}\text{kg}^{-1}$  in group IV at 30% $\dot{V}O_{2\max}$   
 337 between 12 and 13 years, these parameters tend to stabilize in  
 338 groups IV and V (Fig. 4). A difference ( $p < 0.05$ ) was observed  
 339 between groups IV and V at 13 years for  $\dot{V}_E\cdot\text{kg}^{-1}$  at 30% $\dot{V}$   
 340  $O_{2\max}$ . No other significant difference was observed at 13 years  
 341 between groups IV and V.

### 342 **Changes in ventilatory response according to age,** 343 **exercise intensity and sex**

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

13 years and from 13 to 15 years at either 30% ( $p < 0.01$ ), 346  
 60% ( $p < 0.01$ ) or 90% $\dot{V}O_{2\max}$  ( $p < 0.05$ ). No other signifi- 347  
 cant differences were observed for  $V_{T\cdot}$  and fr. 348

Expressed in relative values. No significant difference 349  
 was observed for  $V_{T\cdot}\text{kg}^{-1}$  (Fig. 6). In contrast,  $\dot{V}_E\cdot\text{kg}^{-1}$  was 350  
 significantly higher ( $p < 0.05$ ) between 11 and 13 years in 351  
 boys compared to girls at 30%, 60% and 90% $\dot{V}O_{2\max}$ . No 352  
 significant difference between boys and girls was observed 353  
 between 13 and 15 years. 354

Important note: for the sake of clarity, some results of the 355  
 study were included in the “supplementary material” section 356  
 placed at the end of the manuscript. This supplementary 357  
 data comprise the changes in ventilation according to carbon 358  
 dioxide output and the changes in respiratory carbon dioxide 359  
 equivalent according to oxygen uptake. 360

## 361 **Discussion**

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

### 367 **The effects of age and sex on ventilatory response**

368 Robinson (1938) showed that  $\dot{V}_E$  increased from 6 to  
 369 17 years during a standardized treadmill walk test at con-  
 370 stant intensity. The results of Rutenfranz et al. (1981) cor-  
 371 roborated those of Robinson (1938). They found that  $\dot{V}$   
 372  $E$  increased from 12 to 15 years and then stabilized until  
 373 17 years. While our results, up to 15 years, agree with those  
 374 of Rutenfranz et al. (1981), they showed that  $\dot{V}_E$  increased  
 375 significantly up to age 17 at the highest exercise intensities  
 376 (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)
$\dot{V}_{E_{max}}$ (l.min <sup>-1</sup> )	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 <sup>-1</sup> )	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 <sub>1</sub> (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 ± SEM

$\dot{V}_{E_{max}}$  maximal expiratory flow, MEF maximum expiratory flow, FEV<sub>1</sub> 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  $\dot{V}O_{2max}$ . 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  $\dot{V}O_{2max}$ ) whereas we evaluated  $\dot{V}_E$ ,  $V_T$  and fr at three different intensities (below 30% of  $\dot{V}O_{2max}$ , around 60% of  $\dot{V}O_{2max}$  and above 90% of  $\dot{V}O_{2max}$ ). 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  $\dot{V}O_{2max}$ , 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  $\dot{V}O_{2max}$ . 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  $\dot{V}O_{2max}$ . 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  $\dot{V}O_{2max}$  or between 80 and 85% of  $\dot{V}O_{2max}$ .

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

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**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 <sup>-1</sup> )	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 <sup>-1</sup> )	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 <sub>1</sub> (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, FEV<sub>1</sub> 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

430 V. These differences seem to be directly related to anthropo- 469  
 431 metric characteristics. Indeed, BM and LBM are the 470  
 432 anthropometric characteristics that best explain the 471  
 433 changes in  $\dot{V}_{E_{max}}$  and  $V_{T_{max}}$  during growth (Mercier et al. 472  
 434 1991; Armstrong and Welsman 2020) and BM and LBM 473  
 435 were significantly higher among 13-year-old girls in group 474  
 436 IV (Table 2). However, when  $V_T$  was expressed relatively 475  
 437 to BM (Fig. 4) the significant differences disappeared. 476  
 438 The significant differences in BM and LBM at 13 years 477  
 439 between groups IV and V can probably be explained by 478  
 440 the small number of subjects (*n*=7) in each group of girls 479  
 441 and by heterogeneity in pubertal maturation levels between 480  
 442 girls in groups IV and V. 481

443 Second, the significant increase in  $\dot{V}_E$ , up to 17 years in 482  
 444 boys, was due to a significant increase in VC, and there- 483  
 445 fore,  $V_T$  (Prioux et al. 1997), while fr tended to decrease 484  
 446 (Fig. 1) but without significant change. Robinson's (1938) 485  
 447 results showed that  $V_T$  was 430 ml in the youngest chil- 486  
 448 dren (6 years) and 1.73 l in the oldest (17 years). The study 487  
 449 by Andersen et al. (1974) corroborated these results. They 488  
 450 showed, for a relative intensity between 50 and 60% of  $\dot{V}$  489  
 451  $O_{2_{max}}$ , an increase in  $V_T$  from  $530 \pm 100$  to  $1760 \pm 740$  ml 490  
 452 in boys and from  $460 \pm 120$  to  $810 \pm 100$  ml in girls. Our 491  
 453 study's results appear to be consistent with those outlined 492  
 454 above. Indeed, a significant increase was observed in  $V_T$  493  
 455 from 11 to 13 years, 13–15 years, and 15–17 years, regard- 494  
 456 less of exercise intensity. In girls,  $V_T$  also increased sig- 495  
 457 nificantly from 11 to 13 years and 13–15 years in group 496  
 458 V except for  $V_T$  between 13 and 15 years at 30% $\dot{V}O_{2_{max}}$  497  
 459 (Fig. 2). The fact that the increase in  $V_T$  can be explained 498  
 460 by the increase in VC, as indicated above, agrees with (i) the 499  
 461 significant increase in FEV<sub>1</sub> and VC in boys (Table 5) and 500  
 462 girls (Table 6), (ii) the linear relationships between FEV<sub>1</sub>, 501  
 463 VC and  $V_{T_{max}}$  during growth (Rutenfranz et al. 1981), (iii) 502  
 464 the fact that only half of the lung volume capacity is consid- 503  
 465 ered during maximal exercise (Rutenfranz et al. 1981) and 504  
 466 most importantly (iv) the significant increase in  $V_{T_{max}}$  and 505  
 467 VC up to 17 years, which justifies the stability of the  $V_{T_{max}}/$   
 468 VC ratio between 11 and 17 years (Prioux et al. 1997).

Third, the few studies focusing on fr during growth have 469  
 shown a decrease in fr when age increased. Robinson (1938) 470  
 observed that fr decreased in boys aged 6–17 years. Data 471  
 from Andersen et al (1974) were similar to those of Ruten- 472  
 franz et al. (1981) and confirmed those of Robinson (1938). 473  
 Rutenfranz et al. (1981) have shown that an exercise car- 474  
 ried out at an intensity between 65 and 70% of  $\dot{V}O_{2_{max}}$  in 475  
 children aged 12–17 years induced a decrease in fr from 476  
 39 to 28 breaths.min<sup>-1</sup> in boys and from 38 to 26 breaths. 477  
 min<sup>-1</sup> in girls. These fr values were very close to those 478  
 we observed at 60% of  $\dot{V}O_{2_{max}}$  especially in boys (Fig. 1). 479  
 Andersen et al. (1974) showed a decrease in fr, relatively to 480  
 age, when children aged 8–16 years exercised on a bicycle 481  
 ergometer at 50–60% of  $\dot{V}O_{2_{max}}$  intensity or 70–80% of  $\dot{V}$  482  
 $O_{2_{max}}$  intensity. Rowland and Cunningham (1997) showed 483  
 that fr decreased from 45 to 36 breaths.min<sup>-1</sup> in children 484  
 aged 9–13 years. Finally, Ondrak and McMurray (2006) 485  
 found that fr decreased with age regardless of exercise inten- 486  
 sity. The results we observed in boys (Fig. 1) were consistent 487  
 with those in the literature. Indeed, although not significant, 488  
 fr tended to decrease in all age groups and for each intensity. 489  
 A full longitudinal study conducted from 11 to 17 years of 490  
 age could have shown a significant decrease for this param- 491  
 eter. The results observed in girls are more difficult to inter- 492  
 pret. Indeed, Fig. 2 seems to indicate a tendency of fr to sta- 493  
 bilize during growth. However, the comparison of fr kinetics 494  
 as a function of sex (Fig. 5) showed no significant difference 495  
 between girls and boys, which was consistent with the litera- 496  
 ture (Robinson 1938; Andersen et al. 1974; Rutenfranz et al. 497  
 1981). The trend of fr, with advancing age, would, therefore, 498  
 be to decrease for both girls and boys. 499

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

502 Height is the simplest parameter to measure when evaluat-  
 503 ing growth. It was, therefore, naturally proposed as a deter-  
 504 mining factor in the ventilatory response (Mercier et al.  
 505 1991; Rutenfranz et al. 1981; Rowland 1996). However,

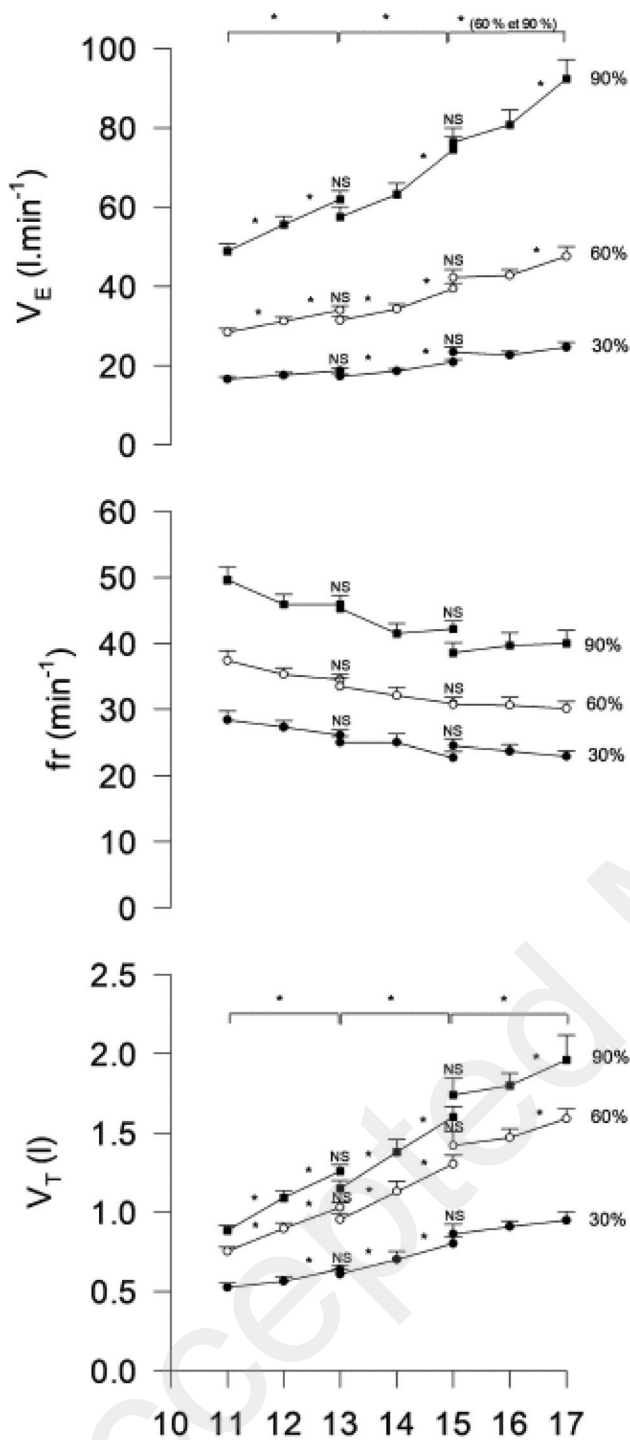


Fig.1 Changes in ventilatory response, expressed in absolute values, as a function of exercise intensity in boys.  $\dot{V}_E$  ventilation,  $fr$  respiratory frequency,  $V_T$  tidal volume; 30%, 60% and 90%: exercise intensity expressed in  $\% \dot{V}O_{2max}$ ; values are means  $\pm$  SEM; \* $p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

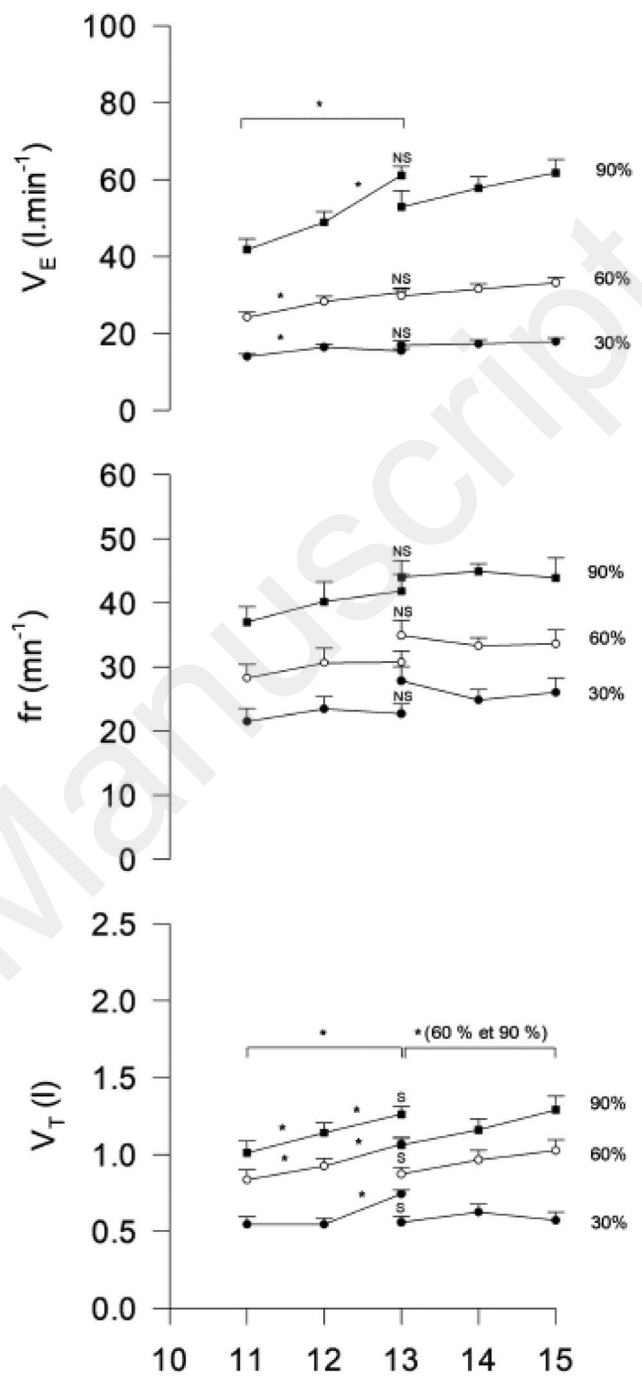
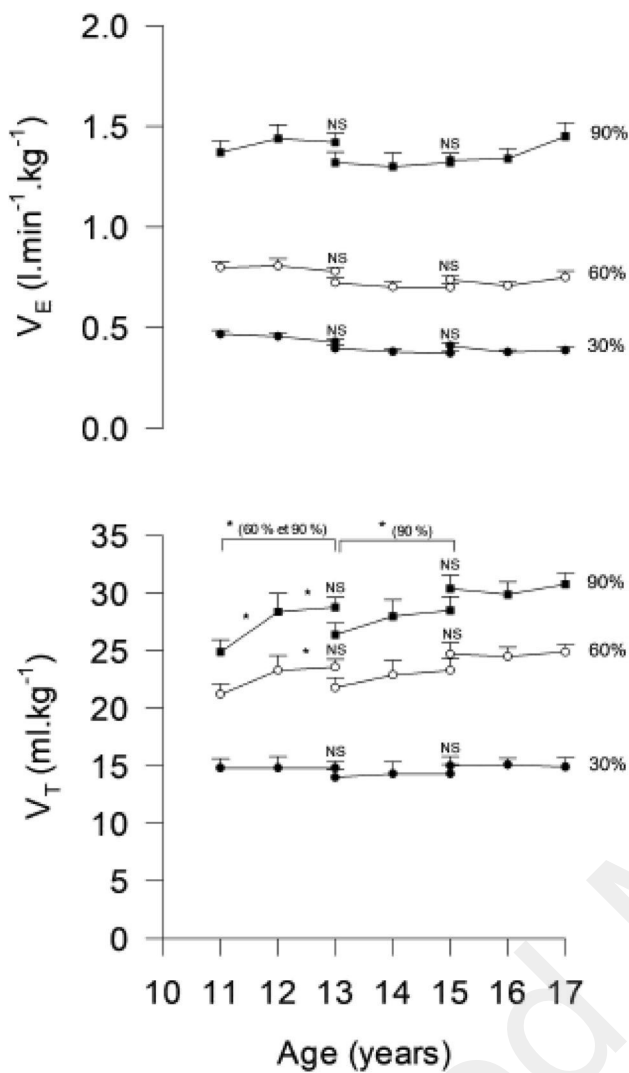


Fig.2 Changes in ventilatory response, expressed in absolute values, as a function of exercise intensity in girls.  $\dot{V}_E$  ventilation,  $fr$  respiratory frequency,  $V_T$  tidal volume; 30%, 60% and 90%: exercise intensity expressed in  $\% \dot{V}O_{2max}$ ; values are means  $\pm$  SEM; \*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

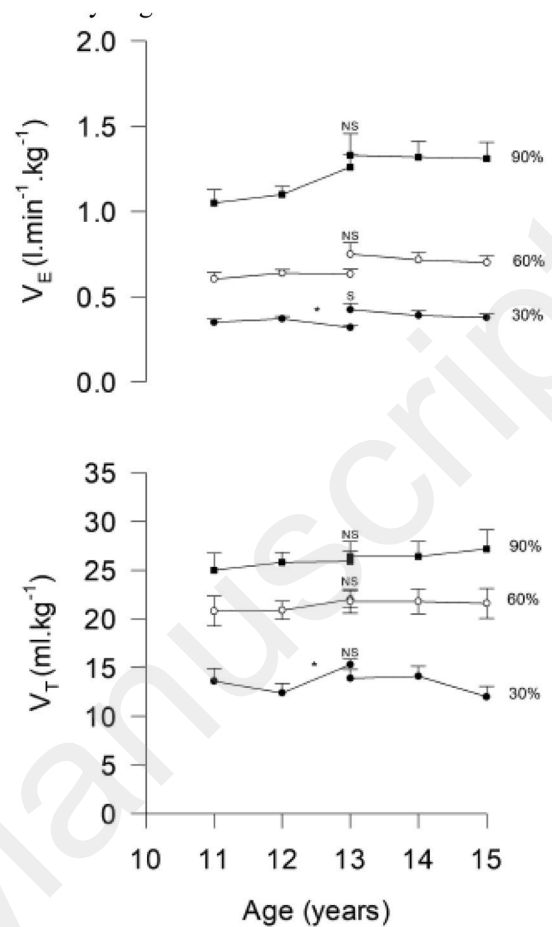
the systematic use of height as a determinant of  $V_{E_{max}}$ , recommended by Rowland, (1996), is relativized by the study of Mercier et al., (1991). Indeed, for these authors, BM and LBM are the anthropometric characteristics that best explain the variations in  $V_{E_{max}}$  and  $V_{T_{max}}$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

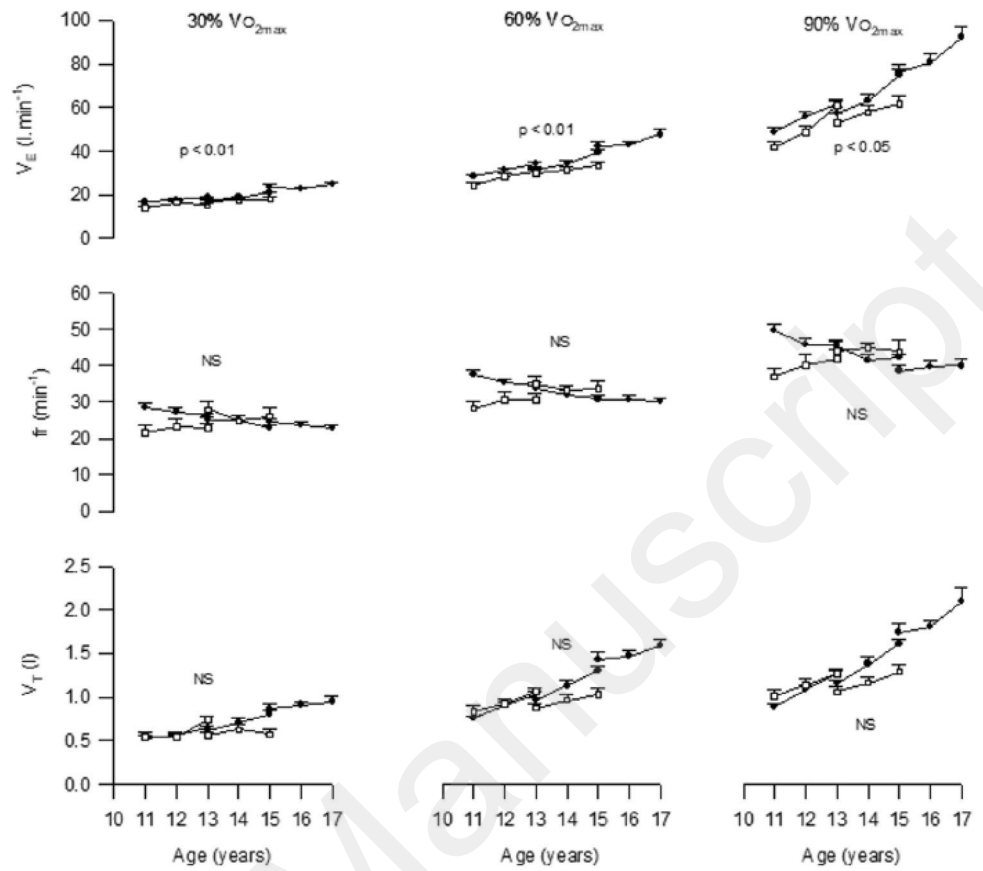
511 growth. Thus, studies such as ours, which propose  $V_{Emax}$   
 512 and  $V_{Tmax}$  values only corrected by BM are not far from  
 513 reality (Armstrong and Welsman 2020). Likewise, the use  
 514 of BM also makes it possible to compare our values with  
 515 those in the literature. Robinson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



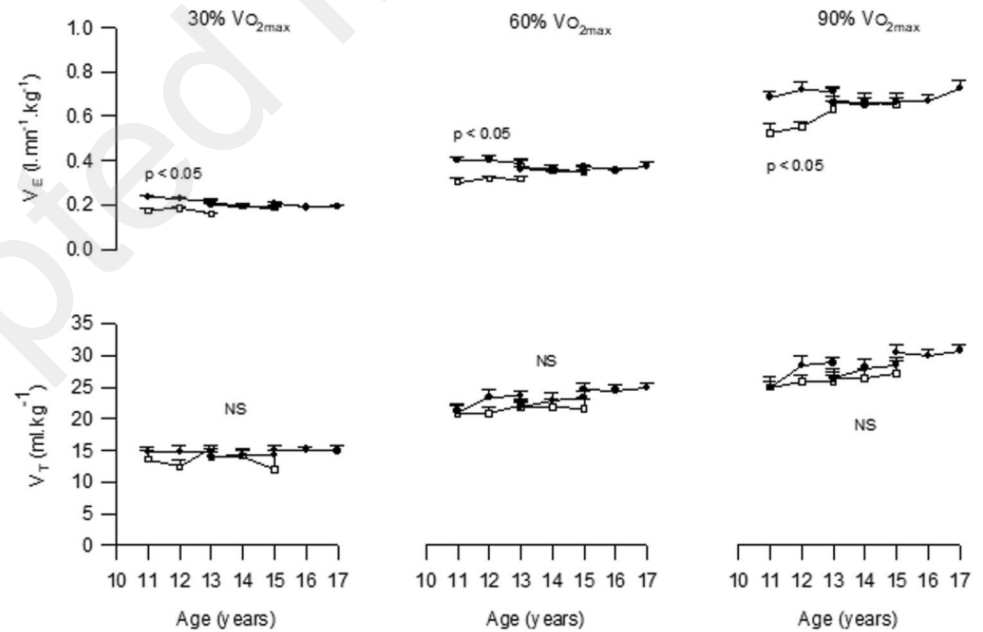
**Fig. 4** Changes in ventilatory response, expressed in relative values, as a function exercise intensity in girls.  $\dot{V}_E$  ventilation,  $V_T$  tidal volume; 30%, 60% and 90%: exercise intensity expressed in  $\% \dot{V}O_{2max}$ ; values are means  $\pm$  SEM; \* $p < 0.05$ ; NS no significant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

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



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

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

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550 showed that  $V_T \cdot \text{kg}^{-1}$  decreased with age, regardless of exer-  
551 cise intensity, in children aged 8–18 years. These results are  
552 not in agreement with those of Rowland and Cunningham  
553 (1997). Indeed, these authors found no significant changes  
554 for  $V_T \cdot \text{kg}^{-1}$  in boys aged 9–13 years. Our results in boys  
555 showed a significant increase in  $V_T \cdot \text{kg}^{-1}$  from 11 to 13 years  
556 at 60% and 90% of  $\dot{V}O_{2\text{max}}$  and from 13 to 15 years at 90%  
557 of  $\dot{V}O_{2\text{max}}$  (Fig. 3). From 15 years of age in group III and up  
558 to the age of 17 years,  $V_T \cdot \text{kg}^{-1}$  no longer increased. These  
559 results suggest that, up to 15 years, the increase in  $V_T$  is  
560 greater than the increase in BM at high intensities (60% and  
561 90% of  $\dot{V}O_{2\text{max}}$ ). BM may, therefore, not be the best anthro-  
562 pometric parameter to consider when studying the changes  
563 of  $V_T$  during growth. The use of LBM appears to be more  
564 appropriate (Mercier et al. 1991; Armstrong and Welsman  
565 2020). However, these results also assume that parameters,  
566 other than anthropometric characteristics, can influence the  
567 changes of  $V_T \cdot \text{kg}^{-1}$  during growth. This does not seem to be  
568 the case for girls. Indeed, except for a significant increase  
569 in  $V_T \cdot \text{kg}^{-1}$  between 12 and 13 years at 30% of  $\dot{V}O_{2\text{max}}$ , our  
570 results showed a remarkable stability of this parameter dur-  
571 ing growth (Fig. 4). Finally, the evolution of  $V_T \cdot \text{kg}^{-1}$  during  
572 growth appears to be independent of sex, since no difference  
573 in  $V_T \cdot \text{kg}^{-1}$  was observed between boys and girls (Fig. 6).

## 574 Strengths and limitations

575 Although breathing pattern data are presented in our study  
576 and helps to explain the changes in ventilation during  
577 growth, we have not fully considered how ventilatory control  
578 may change with age. It would be interesting (i) to add an  
579 index of operating lung volume (i.e., expiratory and inspira-  
580 tory reserve volume) and (ii) to report  $P_a\text{CO}_2$  or more practi-  
581 cally  $P_{\text{ET}}\text{CO}_2$  data. Indeed, these data would provide further  
582 detail regarding exercise ventilatory mechanics (i.e., pres-  
583 ence of dynamic hyperinflation) and ventilatory control (i.e.,  
584 estimates of dead space and alveolar ventilation). In addi-  
585 tion, we should have used a more appropriate experimental  
586 model, such as a real longitudinal study from 11 to 15 years  
587 in girls and from 11 to 17 years in boys, to analyze changes  
588 in ventilatory responses at submaximal exercise intensities  
589 during the growth spurt period (Armstrong and Welsman  
590 2020). Finally, the sample size differs substantially between  
591 boys and girls. Indeed, we have 54 healthy untrained boys  
592 against only 14 healthy untrained girls. Moreover, we have  
593 collected data from 11 to 17 years in boys and only from  
594 11 to 15 years in girls. Despite the validity of our statistical  
595 analyses, it would be interesting to conduct other studies  
596 with more subjects of both sexes and over a longer period,  
597 especially for girls, so that (i) the data can reflect the general  
598 pediatric population in France and (ii) to use these data as  
599 age-specific normative values for exercise performance.

## Conclusion

At submaximal intensities,  $\dot{V}_E$ , expressed in absolute val-  
ues, 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 dur-  
ing 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 signifi-  
cantly lower values in girls compared to boys between 11  
and 13 years, regardless of exercise intensity. In boys,  $V_T \cdot \text{kg}^{-1}$   
 $\text{kg}^{-1}$  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 differ-  
ence of  $V_T \cdot \text{kg}^{-1}$  between boys and girls regardless of age  
and exercise intensity.

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