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

Fenfen Zhou^{1,2,3} · Xiaojian Yin¹ · Kilian Phillipe⁴ · Aya Houssein^{2,3} · Steven Gastinger^{5,6} · Jacques Prioux^{2,3}

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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 _E max	Maximal expiratory time	31
T _I	Inspiratory time	32
T _I max	Maximal inspiratory time	33
T _{TOT}	Total respiratory time	34
T _{TOT}	Maximal total respiratory time	35
T _{TOT} 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}_{E max	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).

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 ± 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 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

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 ± 0.50 to 13.2 ± 0.83 years in group I,
 239 from 12.9 ± 0.71 to 14.8 ± 0.89 years in group II and from
 240 14.9 ± 0.75 to 16.9 ± 0.77 years in group III. Concerning
 241 girls, the measurements were performed from 11.2 ± 0.61
 242 to 13.0 ± 0.57 years in group IV and from 12.9 ± 1.11 to
 243 14.9 ± 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 ± 0.50 years to 13.2 ± 0.83 years)

269 and II (from 12.9 ± 0.71 years to 14.8 ± 0.89 years) in boys
 270 and IV (from 11.2 ± 0.61 to 13.0 ± 0.57 years) and V (from
 271 12.9 ± 1.11 to 14.9 ± 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), $\dot{V}_{E_{max}}$, FEV₁ 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, FEV₁, 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)
$\dot{V}O_{2\text{max}}$ ($\text{l}\cdot\text{min}^{-1}$)	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

313 90% $\dot{V}O_{2\text{max}}$. For V_{T} , 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} , increases ($p < 0.05$) were observed in
 322 group IV at all three intensities. In group V, V_{T} also increases
 323 ($p < 0.05$) but only at 60% and 90% $\dot{V}O_{2\text{max}}$. Finally, fr tended
 324 to stabilize in both groups at all three intensities, with no sig-
 325 nificant change observed. For V_{T} , 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). $V_{\text{T}}\cdot\text{kg}^{-1}$
 330 increased ($p < 0.05$) in group I at 60% and 90% $\dot{V}O_{2\text{max}}$ and in
 331 group II but only at 90% $\dot{V}O_{2\text{max}}$. No other significant changes
 332 in $V_{\text{T}}\cdot\text{kg}^{-1}$ 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 $V_{\text{T}}\cdot\text{kg}^{-1}$ in group IV at 30% $\dot{V}O_{2\text{max}}$
 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 $O_{2\text{max}}$. 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% $\dot{V}O_{2\text{max}}$ ($p < 0.05$). No other signifi- 347
 cant differences were observed for V_{T} and fr. 348

Expressed in relative values. No significant difference 349
 was observed for $V_{\text{T}}\cdot\text{kg}^{-1}$ (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% $\dot{V}O_{2\text{max}}$. 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**

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

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

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

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 ⁻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 ± 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 $\dot{V}O_{2max}$. 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 ⁻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

430 V. These differences seem to be directly related to anthro- 469
 431 pometric 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 ± 100 to 1760 ± 740 ml 490
 452 in boys and from 460 ± 120 to 810 ± 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 FEV₁ and VC in boys (Table 5) and 500
 462 girls (Table 6), (ii) the linear relationships between FEV₁, 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⁻¹ in boys and from 38 to 26 breaths. 477
 min⁻¹ 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⁻¹ 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

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

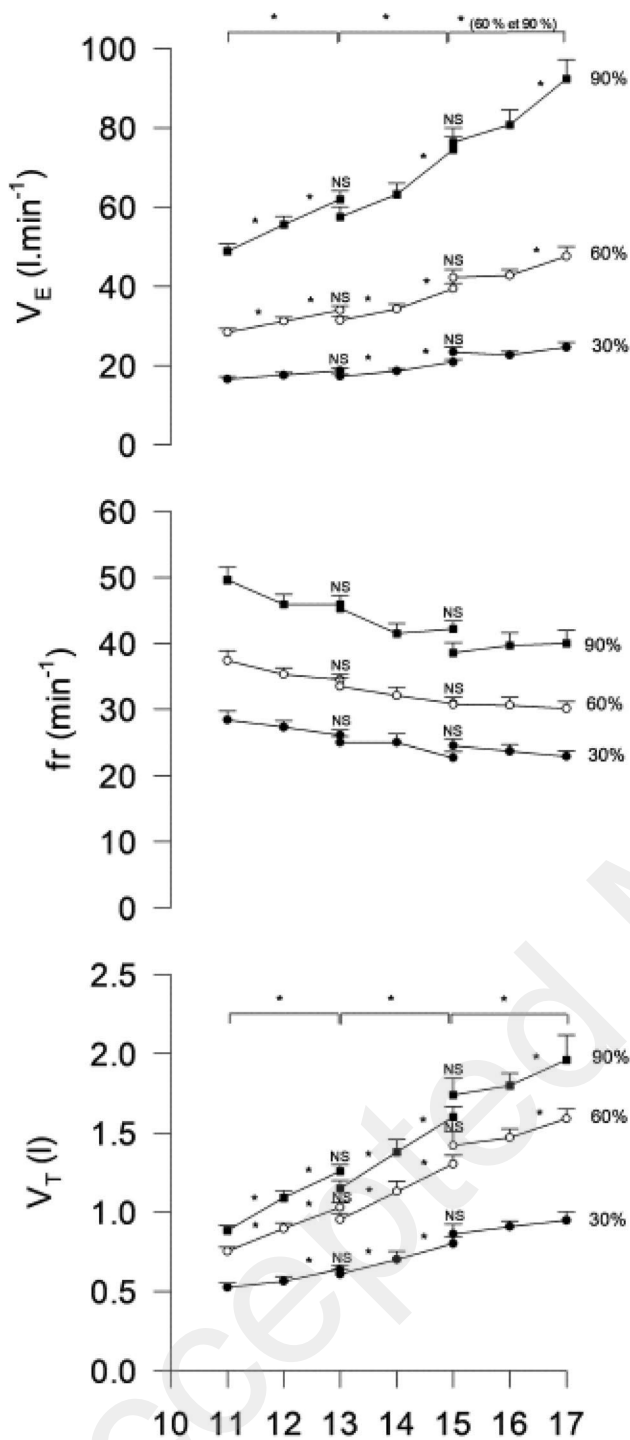


Fig.1 Changes in ventilatory response, expressed in absolute values, as a function of exercise intensity in boys. \dot{V}_E ventilation, fr respiratory frequency, V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in $\% \dot{V}O_{2max}$; values are means \pm SEM; * $p < 0.05$; NS no significant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

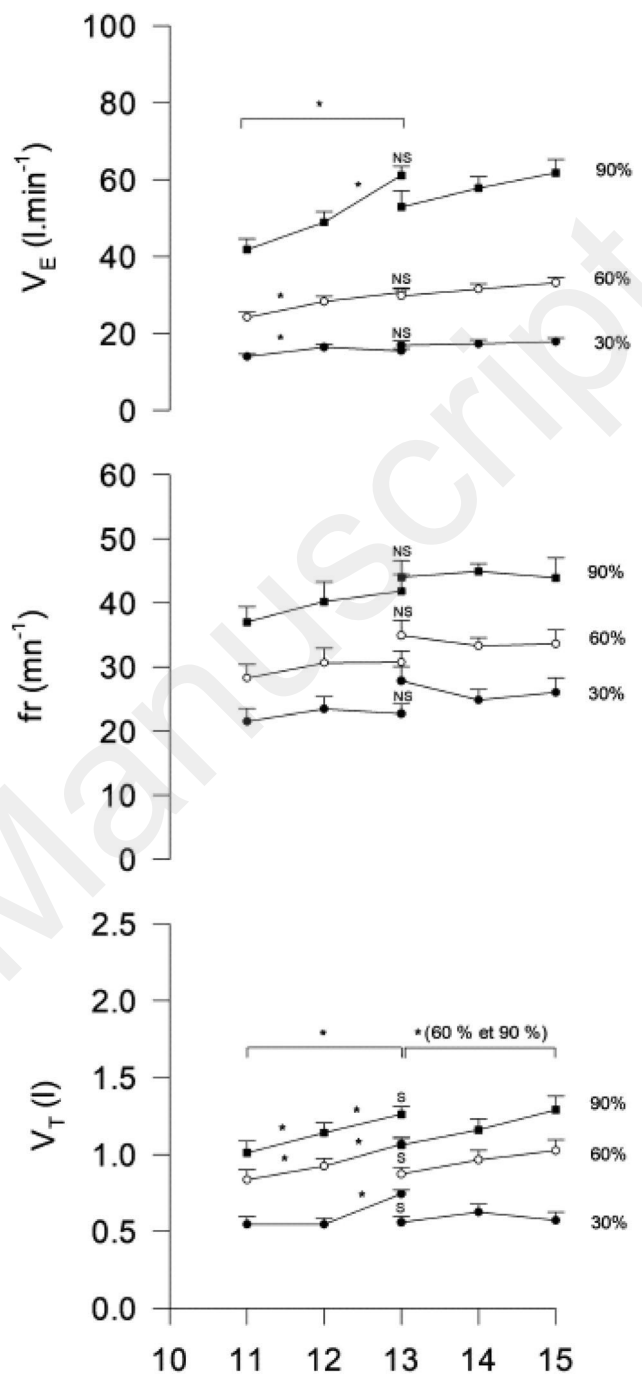


Fig.2 Changes in ventilatory response, expressed in absolute values, as a function of exercise intensity in girls. \dot{V}_E ventilation, fr respiratory frequency, V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in $\% \dot{V}O_{2max}$; values are means \pm SEM; * $p < 0.05$; NS no significant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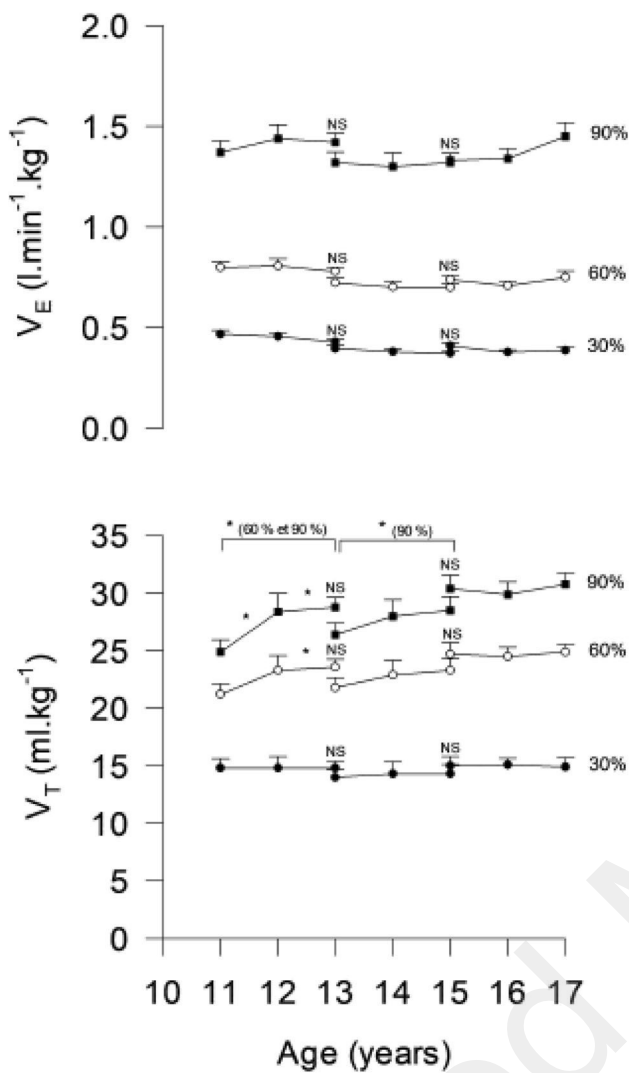


Fig. 3 Changes in ventilatory response, expressed in relative values, as a function of exercise intensity in boys. \dot{V}_E ventilation, V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in $\% \dot{V}O_{2max}$; values are means \pm SEM; * $p < 0.05$; NS no significant difference between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

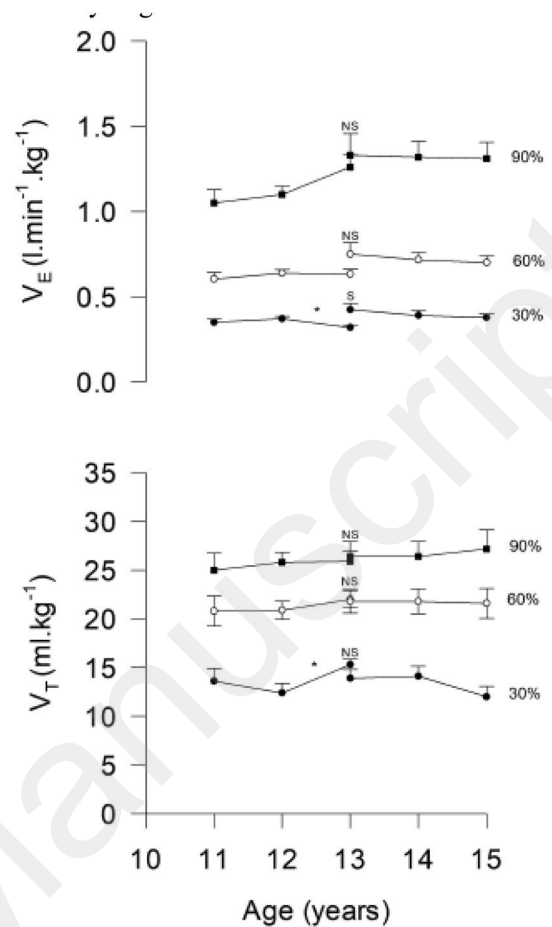


Fig. 4 Changes in ventilatory response, expressed in relative values, as a function exercise intensity in girls. \dot{V}_E ventilation, V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in $\% \dot{V}O_{2max}$; values are means \pm SEM; * $p < 0.05$; NS no significant difference between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

524 in boys (Fig. 3) and girls (Fig. 4) with significantly higher
 525 values in boys between 11 and 13 years, regardless of
 526 exercise intensity (Fig. 6). However, the comparison of
 527 our results with previous studies is questionable. Firstly,
 528 in the studies of Robinson et al. (1938) and Ondrak and
 529 McMurray, (2006) the exercise intensities are expressed in
 530 absolute values. Hence, each workload may have elicited
 531 greater ventilatory responses in the younger and smaller
 532 participants, compared to the older and larger participants.
 533 Secondly, Rowland and Cunningham (1997) focused on
 534 a small number of children (11 boys and 9 girls) and a
 535 relatively small age range (9–13 years). Thus, the variabil-
 536 ity in exercise protocols, the use of different submaximal
 537 intensities, the lack of evaluation of the subjects' body
 538 composition and level of physical activity may contribute
 539 to the variability of the results between the different stud-
 540 ies. The $\dot{V}_E.kg^{-1}$ values proposed in our study can only
 541 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

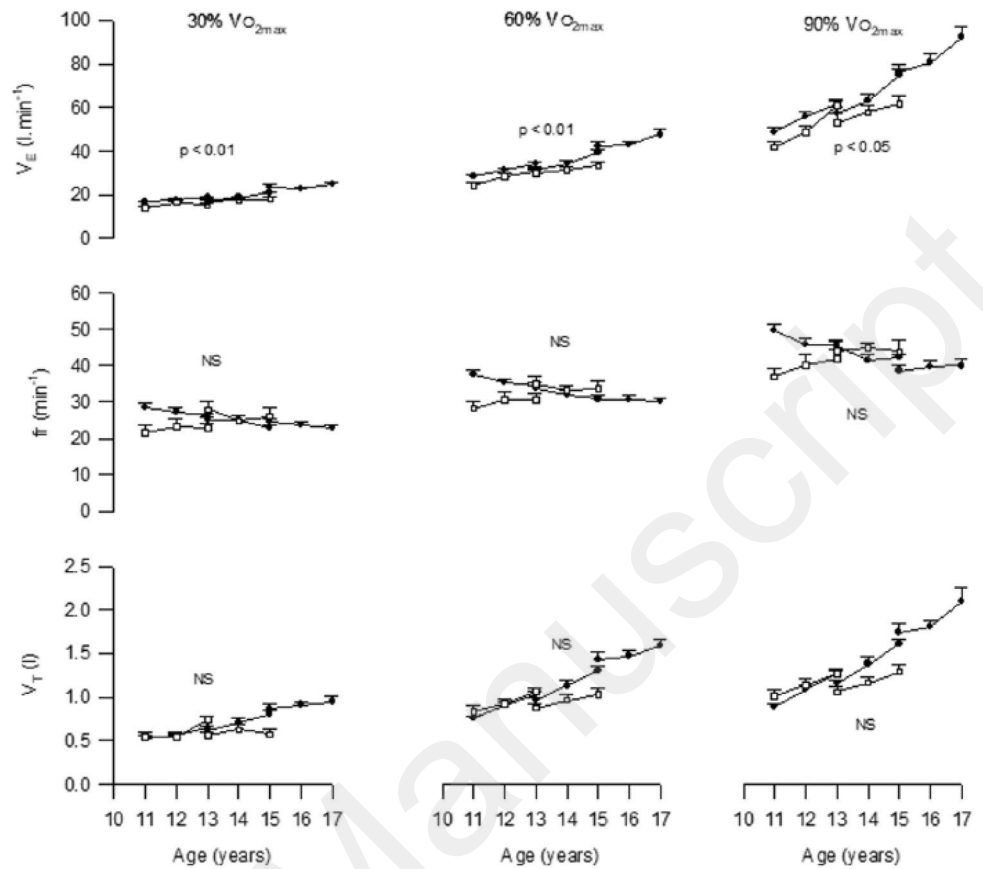
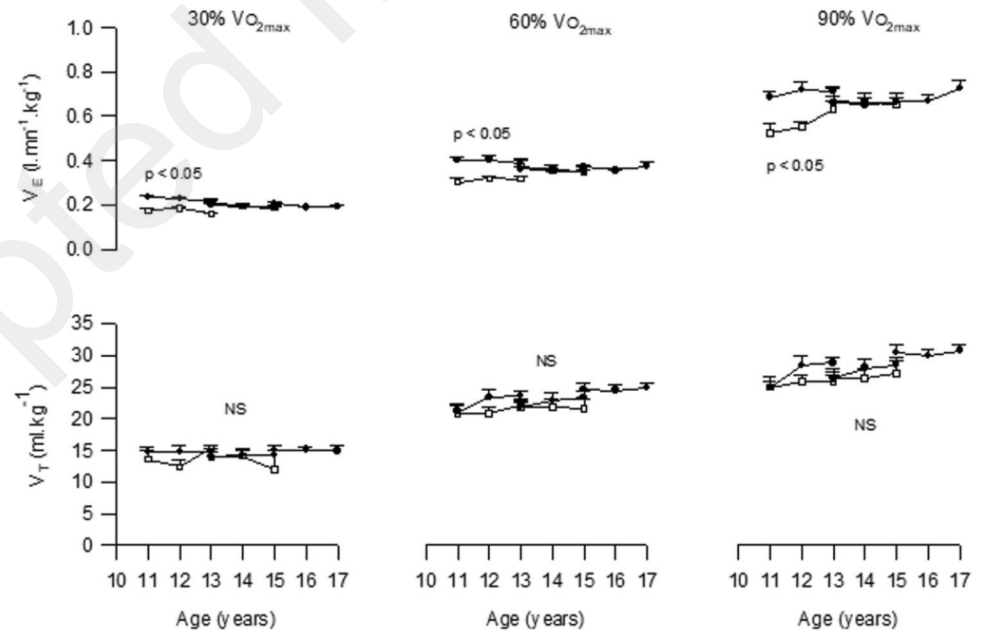


Fig. 6 Changes in ventilatory response, expressed in relative values, as a function of exercise intensity and sex. \dot{V}_E ventilation, V_T tidal volume; 30%, 60% and 90%: exercise intensity expressed in % $\dot{V}O_{2max}$; $\dot{V}O_{2max}$: maximum oxygen uptake; values are means \pm SEM; NS no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



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⁻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)

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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.

600 Conclusion

601 At submaximal intensities, \dot{V}_E , expressed in absolute val-
602 ues, increases between 11 and 17 years in boys and only
603 between 11 and 13 years in girls. Increases in VC, and
604 therefore, in V_T , is the main reason for \dot{V}_E increases dur-
605 ing growth. \dot{V}_E in boys is higher than \dot{V}_E in girls regardless
606 of age and exercise intensity. $\dot{V}_E \cdot \text{kg}^{-1}$ is stable in boys
607 and girls whatever the intensity of exercise with signifi-
608 cantly lower values in girls compared to boys between 11
609 and 13 years, regardless of exercise intensity. In boys, $V_T \cdot \text{kg}^{-1}$
610 increases significantly from 11 to 15 years and then
611 stabilizes until the age of 17 years while $V_T \cdot \text{kg}^{-1}$ tends to
612 stabilize during growth in girls with no significant differ-
613 ence of $V_T \cdot \text{kg}^{-1}$ between boys and girls regardless of age
614 and exercise intensity.

615 **Supplementary Information** The online version contains supplemen-
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623 Jacques Prioux, Kilian Phillipe, Aya Houssein, Steven Gastinger and
624 all the authors commented on previous versions of the manuscript. All
625 the authors provided critical feedback and helped shape the research,
626 analysis and manuscript.

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