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Inter-individual differences in breathing pattern at high levels of incremental cycling exercise in healthy subjects

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ABSTRACT

Interindividual differences in the rate of changes in tidal volume (V_T) and respiratory frequency (f_R) were examined during a maximal incremental cycling exercise. The gain of the inspiratory off-switch reflex was inferred from the V_T vs. inspiratory duration (T_i) relationship. Some subjects also executed a static handgrip exercise, used as a "non-dynamic" exercise trial to study patterning of breathing.

Above the ventilatory threshold (V_{Th}), two patterns of response were identified: in group 1, the rate of change in V_T significantly increased, while in group 2 the breakpoint of ventilation solely resulted from f_R increase. After the respiratory compensation point, a tachypnoeic response always occurred. A leftward shift of the V_T vs. T_i relationship, i.e., an inspiratory off-switch reflex, was measured during the handgrip in group 2 subjects as well as marked f_R variations.

Our study identifies two different patterns of breathing after the V_{Th}. The subjects who present a tachypnoeic response to exercise above the V_{Th} have a higher sensitivity to pulmonary inflation and their tachypnoeic response was ubiquitous during a maximal handgrip test.

1. Introduction

The time course of hyperventilation during an incremental exercise has already been intensively explored in previous studies (Wasserman et al., 1973; Jones, 1988). Three phases in the ventilatory (V_E) response can be discerned: the first one is characterized by a linear relationship between $\dot{V}_E$ and oxygen uptake ($\dot{V}_{O_2}$). In the second one, $\dot{V}_E$ increases more than $\dot{V}_{O_2}$ (SV1 or ventilatory threshold, V_{Th}), and in the third one, V_E increases more than $\dot{V}_{CO_2}$ (SV2 or respiratory compensation phase, RCP). Because $\dot{V}_E$ represents the product of the tidal volume (V_T) and respiratory frequency (f_R), many investigators have described the mean typical changes in the pattern of breathing, during an incremental exercise (Gallagher and Younes, 1986; Jones, 1988; Scheuermann and Kowalchuk, 1999; Whipp and Pardy, 1986; Younes and Kirvinen, 1984). These studies suggest that the pattern of breathing evenly varies during an incremental exercise, the V_T increase reaching a plateau when V_T levels off 50% to 60% of the forced vital capacity (FVC) while f_R remains stable or slightly increases. As the exercise proceeds, a further $\dot{V}_E$ increase occurs due to f_R increase, which is called "the tachypnoeic shift". More recently, Naranjo et al. (2005) proposed a nomogram based on a sample of 64 subjects, giving an exponential relationship between V_T and f_R.

On the other hand, our experience of breathing pattern analyses during an incremental cycling exercise in healthy subjects strongly indicates a large inter-individual variability of V_T and f_R changes. An extensive analysis of the literature data confirms this inter-individual variability. Indeed, Blackie et al. (1991) reports in 231 normal subjects a wide range of values of the ratio between the maximal V_T measured at the end of exercise and the functional residual capacity (FVC), the V_{Tmax}/FVC ratio ranging from 38% to 72%. Moreover, Lucia et al. (1999), analysing the changes in breathing pattern of highly competitive cyclists, have shown that the tachypnoeic shift was not present in all their subjects. Recently, Cross et al. (2012) have identified in 28 healthy subjects, using the polynomial spline smoothing method, two successive disproportionate changes in the f_R vs. $\dot{V}_{O_2}$ relationship, the second one being closely correlated with the RCP. They also reported that the V_T plateau inconstantly occurred and was measured at the V_{Th} in 14/28 subjects and at the RCP in 18/28 subjects. These recent data support our observations of a scattering of breathing pattern changes in healthy subjects performing an incremental exercise.

The first aim of this study was to identify typical changes in breathing pattern in healthy normal male subjects who underwent an incremental cycling exercise. The changes in breathing pattern after V_{Th} and RCP were highlighted and the reproducibility of inter-individual differences was examined. The second aim was to approach the possible mechanisms of these differences. We

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formulated the hypotheses that the inter-individual discrepancies between the magnitude of V_T and f_R increases could result from (1) a mechanical limitation of inspiration in relation with the individual value of the maximal inspiratory capacity and/or (2) different gains of the vagal inspiratory off-switch reflex mechanism which limits the pulmonary hyperinflation (Clark and von Euler, 1972). We also hypothesized that the inter-individual variations of the breathing pattern response to exercise may occur in other circumstances of stimulation of the respiratory centers. Thus, we explored in some subjects their respiratory response to a sustained static handgrip trial which constituted a second mode of exercise trial to study patterning of breathing.

2. Materials and methods

2.1. Ethical approval

The protocol was approved by the Ethics Committee of our institution (CCPPRB Marseille 1). The study conformed to the standards set by the latest revision of the *Declaration of Helsinki*. The procedures were carried out with the adequate understanding and written consent of the subjects.

2.2. Subjects

A total of twenty eight male subjects were explored. They were considered sedentary subjects because they did not participate in regular formal exercise. Their morphological characteristics and breathing pattern at rest are shown in Table 1. At their inclusion in the study, pulmonary function tests were performed. A total body pressure plethysmograph (Masterlab, Jaeger, Bunnik, The Netherlands) allowed us to determine the maximal lung volumes, that are the forced vital capacity (FVC), the total lung capacity (TLC), and also the functional residual capacity (FRC). All these data are shown in Table 1.

Table 1
Morphological and, respiratory characteristics, and exercise performances of healthy subjects separated in two groups according to the differences in the breathing pattern changes during incremental cycling exercise. Values are the mean ± SEM.

	Group 1	Group 2
N	10	18
Age, year	43.4 ± 3.7 [26–68]	32.9 ± 3.2 [19–63]
Weight, kg	80.1 ± 3.5	76.6 ± 2.2
Height, cm	177.8 ± 2.4	180 ± 1.3
f_H, min^{-1}	70 ± 3.1	76.7 ± 2.7
$\dot{V}_E$, LBTPS min^{-1}	12.2 ± 1	11.4 ± 0.6
V_T, LBTPS	0.809 ± 0.1	0.725 ± 0.04
f_R, min^{-1}	17 ± 1.3	16.8 ± 1
TLC, LBTPS	7.6 ± 0.3	7.26 ± 0.33
FVC, LBTPS	5.4 ± 0.2	5.1 ± 0.3
IC, LBTPS	4 ± 0.2	3.7 ± 0.2
FRC, LBTPS	3.6 ± 0.3	3.5 ± 0.2
Ventilatory threshold		
Time, s	357 ± 21	441 ± 44
Power, W	136 ± 10	160 ± 31
$\dot{V}_{O_2}$, mlSTPD min^{-1} kg^{-1}	22 ± 1	25 ± 2
$\dot{V}_{O_2}$, %$V_{O_2 max}$	62 ± 2.7	67 ± 2
Respiratory compensation point	*n* = 6	*n* = 9
Time, s	636 ± 53	640 ± 81
Power, W	220 ± 16	222 ± 28
$\dot{V}_{O_2}$, mlSTPD min^{-1} kg^{-1}	31 ± 3	37 ± 4
$\dot{V}_{O_2}$, %$V_{O_2 max}$	85 ± 2.3	88.6 ± 1.4
End exercise	*n* = 10	*n* = 18
Power, W	224 ± 15.1	244 ± 17.3
$\dot{V}_{O_2 max}$, ml min^{-1} kg^{-1}	36 ± 2.2	37 ± 2.6

V_E: ventilation; V_T: tidal volume; f_R: respiratory frequency; f_H: cardiac frequency, TLC: total lung capacity, FVC: Forced vital capacity, IC: inspiratory capacity, FRC: functional residual capacity, BTPS: body temperature pressure saturated condition; $\dot{V}_{O_2}$: oxygen uptake.

2.3. Measurements of respiratory variables and heart rate

For breath by breath analyses of $\dot{V}_E$, V_T and f_R, we used a turbine flow-meter connected to a face mask (dead space: 30 ml) which was designed to form an air-tight seal over the patient's nose and mouth. A sampling catheter connected the outlet of the mask to fast-response differential paramagnetic O_2 and infrared CO_2 analyzers (90% response time in 100 ms) which measured end-tidal partial pressures of O_2 (P_{ETO_2}) and CO_2 (P_{ETCO_2}), respectively (Oxycon beta, Jaeger, Bunnik, The Netherlands). The microcomputer software (Oxycon beta, Jaeger, Bunnik, The Netherlands) averaged for 5 consecutive seconds data of ventilation ($\dot{V}_E$), tidal volume (V_T), breathing frequency (f_R), inspiratory duration (T_i), and the T_i/T_{tot} ratio. The software also computed the oxygen uptake ($\dot{V}_{O_2}$), the CO_2 production ($\dot{V}_{CO_2}$), and the ventilatory equivalents for O_2 ($Eq_{O_2} = \dot{V}_E/\dot{V}_{O_2}$) and CO_2 ($Eq_{CO_2} = \dot{V}_E/\dot{V}_{CO_2}$). A calibration procedure for the flow meter and gas analyzer systems was carried out before each test. At rest, the data were averaged for a 10-min period. The percutaneous oxygen saturation (Sp_{O_2}) was continuously measured throughout the exercise challenge and the recovery period using an infrared analyser (Nellcor model N3000, TX, USA). ECG was continuously recorded from standard ECG leads and the cardiac frequency (f_H) was computed.

2.4. Cycling exercise

Each subject performed an incremental exercise test on an electrically braked cycle ergometre (Ergometrics ER 800, Jaeger, Bunnik, The Netherlands). In all the subjects, the exercise protocol consisted of: (1) a 10-min rest period, during which all the variables were averaged, (2) a 2-min 0-W work load period used to reach the 1 Hz pedaling frequency, (3) a work period. The work period started at a work load of 20 W and the load was increased by 20 W every 1 min until the subject stopped pedaling. Two operators visually determined the V_{Th} and RCP from Eq_{O_2} and Eq_{CO_2} data. V_{Th} corresponded to the $\dot{V}_{O_2}$ value at which Eq_{O_2} exhibited a systematic increase without a concomitant increase in Eq_{CO_2} (Wasserman et al., 1973). RCP was determined if the Eq_{CO_2} curve began to rise. This corresponded to a second breakpoint on the V_E versus time curve. V_{Th} and RCP breakpoints were independently determined by the two operators. When we could not meet the three criteria we rejected the RCP data analyses. The difficulties encountered to determine the RCP breakpoint did not bias our study because, as shown in results, the inter-individual variations of the breathing pattern (f_R and V_T) were only detected at the V_{Th}. Because the data were averaged for 5 consecutive seconds, the inter-operator differences in breakpoints determination, when they occurred, never exceeded 10–15 s. In such a case, we decided to choose the intermediate epoch to determine the breakpoint. V_{Th} and RCP were expressed in absolute value of oxygen uptake related to the body weight. The peak $\dot{V}_{O_2}$ value ($\dot{V}_{O_2 max}$) was measured when the subject had reached his predicted maximal cardiac frequency (220 − age). The reproducibility of the breathing pattern changes during the incremental exercise was tested in nine subjects who repeated twice at a two months interval the cycling protocol.

2.5. Determination of the different ventilatory patterns

The different components of the breathing pattern ($\dot{V}_E$, V_T, f_R) as well as the f_H value were plotted against the oxygen uptake,