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Gas exchange readjustments in response to hypoxia and hypercapnia exposure in Magadan region military service draftees

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Abstract

Object. Our study identified gas exchange and external respiration characteristics during hypoxia and hypercapnia exposure in young men of the Magadan Region.

Materials and methods. A comprehensive survey in young men of military age, 18-21 yr., permanent residents of the Russia's Northeast, was conducted. A hypoxic-&-hypercapnic respiration test with no CO_2 absorption was used. Before and after respiration, using indirect calorimetry method, we analyzed gas composition in exhaled air, external respiration variables, body energy expenditure at rest, respiratory quotient, ventilation equivalents for oxygen and carbon dioxide (Carbonic gas analyzer, Medgraphics VO2000 gas meter). Statistical data processing was performed with Statistica 7.0 package.

Results. Significant post-respiratory dynamics in most indicators of gas exchange and external respiration was found. In response to hypoxia and hypercapnia effects, an increase in the energy consumption at rest, in minute volume of body temperature and pressure saturation, in carbon dioxide emission and oxygen consumption per minute was observed with significantly decreased oxygen utilization factor.

Conclusion. Effects of hypoxic-&-hypercapnic test can be seen as pronounced readjustments in analyzed variables: intensed metabolism at the test peak and that reduced below baseline in the recovery period. In this case, breathing patterns are readjusted with pronounced increase in pulmonary ventilation and higher values in breathing depth in comparison with the baseline value at each stage of the recovery period, up to its 3rd minute.

Keywords

Young men, Gas exchange, Hypercapnia, Hypoxia, Rebreathing, Indirect calorimetry

Imprint

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Introduction

In scientific community, hypoxic and hypercapnic stimuli are supposed to reinforce each other in the regulation of physiological functions [1, 2, 3]. In fact, hypoxia with no hypercapnia does not cause breathing activation [2, 4, 5]. The respiratory system is mainly responsible for achieving and maintaining an appropriate arterial blood gas composition that is the tension of oxygen (Po2) and carbon dioxide (Pco2), thus to a certain extent, the hydrogen ion concentration [6].

Hypoxic and hypercapnic stimuli have an adaptive influence which intensifies the physical performance, and enhances the cardiovascular and respiratory functional capabilities [2]. Previous investigations on inhalation of mixture with higher amount of carbon dioxide proved the combined action of hypoxic-hypercapnic stimuli only to be able to maintain the proper internal environment of the body [7].

The average intensity of the hypercapnia and hypoxia effects, as well as their various combinations, has a compensatory importance in developing body adaptive responses since it improves the mechanisms of resistance to extreme factors [1]. Chemo-reflex demonstrates dominance in ventilation and cardiovascular autonomic regulation. Peripheral carotid chemoreceptors respond primarily to hypoxia [8, 9] while brain chemoreceptors respond primarily to hypercapnia [10].

Indirect calorimetry is widely used for measuring energy consumption, both at resting and functional tests that study energy homeostasis. This method most accurately assesses gas exchange responses and readjustments [11].

This study examined young men to investigate gas exchange responses under rebreathing test.

Materials and methods

Forty three males of military age, 18–21 yr., participated in the Magadan Region Military Commissariat

Training and Conscription Department Survey. The mean age was 20.0±0.3 yr. A rebreathing test with no CO_2 absorption was used as a functional exercise. Subjective baseline exhaled O_2 and CO_2 values (%) were determined using the Carbonic gas analyzer. During the test, each subject made three deepest possible exhalations into the Douglas type bag. Further breathing was performed from that sealed bag for three minutes with the nose closed with a clip [12]. After the test completion, the gas mixture left in the bag was analyzed for the CO_2 and O_2 percentage amount.

We used the Medgraphics VO2000 metabolograph to analyze gas exchange and respiratory system parameters prior to the rebreathing test, at its peak, as well as at 2nd and 3rd minutes of the recovery. Energy consumption (Kcal, kcal/min; REE, kcal/day), their percentage to standard level (REE/Pred, %), respiratory volume (V_t BTRS, mL), respiration rate (RR, cycle/min), respiratory minute volume (VE BTRS, L/min), respiratory quotient (RQ, arb. units), oxygen consumption and carbon dioxide production rates (VO_2, VCO_2, mL/min) in ratio to respiration rate (VO_2, VCO_2, mL/RR), exhaled oxygen and carbon dioxide concentration ($FETO_2$, $FETCO_2$, %), oxygen and carbon dioxide ventilation equivalent (VE/VO_2, VE/VCO_2), and oxygen utilization factor (Ox. Util. Fact., mL/L) were calculated.

Results were processed with Statistica 7.0. The Shapiro-Wilk test was used to check out distribution of measured variables for normality. Results of parametric processing methods were presented as the mean value and its error (M±m). Statistical significance for differences was determined with the Student's t-criterion for dependent samples. The critical level of significance was taken to be equal to or less than 0.05.

Results

Table 1 attached hereto shows data on indirect calorimetry at rest, after rebreathing, as well as at 2nd and 3rd minutes of the recovery period. We can observe significant dynamics through nearly all studied gas exchange indicators in the post-rebreathing period. The hypoxia and hypercapnia study showed statistically significant increase in Kcal, REE, REE/Pred, RR, VE BTRS, the CO_2 production per minute (VCO_2), the O_2 consumption per minute (VO_2), as well as correlation of those values with the respiratory rate, VE/VO_2, and the oxygen concentration for each subject in the air they exhaled (FET O_2) with a significantly lowered oxygen utilization factor.

The following subjective variables demonstrated a statistically significant decrease at the second minute of the recovery period as compared to those in

Table 1

Indirect calorimetry in 18-21 year old males at rest and different stages of post rebreath

Indicators	Stage of Test				Difference Significance Level			
	Baseline	Post Rebreathing	2nd min after Test	3rd min after Test	Baseline-1st min	1st min-2nd min	2nd min-3rd min	Baseline-3rd min
KCal (kcal/min)	1,37±0,04	1,93±0,13	1,43±0,07	1,22±0,05	p<0,001	p<0,001	p<0,05	p<0,05
REE (kcal/day)	2001,2±61,5	2875,9±189,7	2141,0±97,9	1847,9±66,8	p<0,001	p<0,001	p<0,05	p<0,05
RQ (arb. units)	0,78±0,02	1,00±0,03	1,01±0,02	0,96±0,02	p<0,001	p=0,74	p=0,10	p<0,001
REE/Pred (%)	111,5±2,9	161,4±11,3	120,5±5,4	103,3±3,4	p<0,001	p<0,001	p<0,01	p<0,05
RR (cycle/min)	16,5±0,7	16,7±0,8	16,2±0,6	15,5±0,6	p=0,90	p=0,63	p=0,50	p=0,29
V_t BTPS (mL)	575,4±22,2	882,6±62,4	706,7±31,3	632,8±30,1	p<0,001	p<0,05	p<0,05	p<0,05
VE BTRS (L/min)	8,6±0,2	14,3±0,9	11,4±0,5	9,9±0,4	p<0,001	p<0,01	p<0,05	p<0,01
V CO_2 (mL/RR)	15,1±0,8	25,6±2,2	19,6±1,7	18,3±1,1	p<0,001	p<0,05	p=0,52	p<0,05
V CO_2 (mL/min)	224,7±8,6	383,4±22,7	299,1±12,3	247,3±10,1	p<0,001	p<0,01	p<0,01	p<0,05
V O_2 (mL/min)	289,4±8,9	398,9±27,9	295,8±13,4	256,1±9,3	p<0,001	p<0,01	p<0,01	p<0,01
V O_2 (mL/RR)	19,4±0,9	26,3±2,3	19,6±1,8	19,4±1,4	p<0,001	p<0,05	p=0,91	p=0,99
VE/VCO_2 (arb. units)	39,4±1,0	37,6±1,0	38,7±0,8	39,6±1,0	p=0,21	p=0,39	p=0,48	p=0,88
VE/VO_2 (arb. units)	30,3±0,8	37,7±1,6	38,8±1,2	38,1±1,4	p<0,001	p=0,59	p=0,69	p<0,001
FET CO_2 (%)	3,3±0,1	3,4±0,1	3,3±0,1	3,1±0,1	p=0,26	p=0,14	p=0,26	p=0,17
FET O_2 (%)	16,7±0,1	17,2±0,1	17,5±0,1	17,5±0,1	p<0,01	p=0,12	p=0,94	p<0,001
Ox. Util. Fact. (arb. units)	34,1±0,9	28,8±1,3	26,8±0,9	26,8±0,9	p<0,001	p=0,21	p=0,99	p<0,001

the post-rebreathing period: Kcal, REE, REE/Pred, V_t BTPS, VE BTRS, VCO_2 (mL/min), VO_2 (mL/min), VCO_2 (mL/RR), and VO_2 (mL/RR) with no changes observed in RR, VE/VO_2, and Ox. Util. Fact. At the third minute of the recovery, the values of V_t BTPS, VE BTPS, and VCO_2 (mL/min) were significantly lower than those recorded at the second minute, but still higher than the resting values, which suggested an incomplete recuperation in comparison with the baseline. We could also observe an incomplete, vs. the baseline, recovery in RQ, VCO_2 (mL/RR), VE/VO_2, FET O_2, and Ox. Util. Fact. values at the third minute after the test. No significant dynamics was found in RR, VE/VCO_2, and FET CO_2 through all stages of the experiment.

Our results obtained indicate complicated diversified patterns in the gas analysis and the external respiration readjustments in response to hypoxic-&-hypercapnic exposure. We examined the peak values and found 7.4±0.2 % of carbon dioxide and 12.2±0.2 % of oxygen in the collecting bag after test, which made it only possible to use their own metabolic CO_2 to make hypercapnic effects. Under the rebreathing test, the subjective breathing patterns tended to change with running VE BTRS (pulmonary ventilation) due to higher V_t BTRS and with no changes in RR compared to the baseline values.

The growth of V_t BTPS occurs by using reserve volume of inhalation and exhalation, i.e., by a stronger contraction of the respiratory muscles, which provides deeper breathing. Greater importance of V_t BTPS in pulmonary ventilation (VE BTPS) indicates more reserve capabilities of the respiratory system and some effective patterns of adaptation which develop under loads [1]. The rebreathing peak significantly (by 70%) raised the CO_2 values, which remained high in the recovery period in comparison with the resting values. Carbon dioxide being the final product of metabolism develops biochemical reactions since it is a pronounced stimulator of the central nervous system, hemodynamics, the vascular tone, and it is also important in the regulation of the gas exchange and respiration functions [13, 14, 15].

The gas exchange chemo-regulation mechanism controls respiratory system functioning and is aimed at maintaining the proper partial pressure of carbon dioxide in the red blood cell mass [16]. It is known that the fastest way to reduce the amount of CO_2 in the body is to increase the ventilation function of the lungs [17]: chemoreceptors produce a significant effect on the broncho-pulmonary system activity, since they sensitively react even to slight changes in the chemical composition of blood washing them [18]. Being in their excited state, the chemoreceptors contribute to meeting the body metabolic needs by intensifying the respiratory system activity [18]. The VE/VCO_2 indicator is a carbon dioxide ventilation equivalent; it reflects the ventilation needs for a specific amount of produced CO_2 [19] and is currently considered as a marker of the chemo-reflecting sensitivity [20]. Changes which occur in a linear relation between VE and carbon dioxide removal (VE/VCO_2) are currently used for estimating the ventilation efficiency [21].

In our survey, we observed the test-peak-accelerated (by 66 %) pulmonary ventilation that fully removed excessive carbon dioxide, which was confirmed by zero dynamics in the carbon dioxide ventilation equivalent in response to the rebreathing test. The increased ventilation per minute (VE) and the CO_2 removal during the hypoxia-hypercapnia test are necessary for the homeostatic pH control in the body. Besides, that eventually reduces arterial PCO_2 [17]. The oxygen consumption rate (VO_2) is the main characteristic of the gas exchange. However high VO_2 values reflect metabolic processes in the body rather than the external respiration and thus indicate a significant intensification of metabolism [22]. A hypoxic-hypercapnic exposure increases the body oxygen needs, which can be seen in an increased (by 34 %) rate of its consumption and the lowered VO_2 values in the recovery period as compared to the baseline.

G. Karaterzi in some works (2011) also indicates a reduction in the oxygen consumption after hypoxic training, which suggests a more efficient use of oxygen by tissues, a lower metabolic demand [23], and evaluates tissue adaptation to lack of O_2 [24]. According to F. Joulia (2002), hypoxemia and hypercapnia are associated with a reduced oxygen uptake [25].

The oxygen ventilation equivalent (VE/VO_2) values determine respiratory needs at a given level of the O_2 utilization [19]. In our survey, we obtained fairly low resting oxygen equivalent values (VE/VO_2), significantly lower than those given in other authors' studies [26]. At the same time, we observed higher VE/VO_2 in response to the rebreathing test, which indicated the lowered respiration efficiency and was confirmed by the decreasingly low oxygen utilization factor. The VE/VO_2 and oxygen util. factor dynamics is associated with the gas exchange energy metabolic indicators that is significantly reduced in the recovery period (vs. the baseline and the peak values): Kcal, REE, and REE/Pred which are commonly used in scientific papers abroad as some criteria for metabolic adaptation, as well as the so called price of energy costs in people living in different climatic and geographical regions including the circumpolar zones [27]. In this context, our data are fully consistent with those indicated by those authors who associate low REE values after hypoxia with the energy conservation needs in order to prevent further energy loss due to a reduced oxygen consumption, which can be caused by lowered excitability in hippocampal neurons in the brain after hypoxia [28].

The overall dynamics of the carbon dioxide removal rate does not correspond to the changes in the oxygen consumption rate described above. At the peak of the test, VCO_2 increases by 70% versus the 34% increase in the rate of the oxygen consumption. The VCO_2/VO_2 ratio reflected in the respiratory quotient (RQ), which assesses the metabolic processes, tends to rise at the peak, but not to reduce in the recuperation.

Discussion and conclusions

The gas exchange readjustments caused by the combined hypercapnia and hypoxia exposure influence breathing patterns, which can be seen in accelerated metabolism at the peak states of the test and the reduction in the recovery. The respiration system demonstrates more pronounced pulmonary ventilation with deeper breathing as compared to the baseline value at any stage of the recovery period, up to the 3rd minute. In addition, our study has confirmed the previously described findings about the reduced oxygen consumption after the hypoxia and hypercapnia test. The ventilation equivalent values demonstrate their multidirectional changes, with no significant dynamics for carbon dioxide at all stages of the study, but significant and pronounced changes for oxygen observed in the post-rebreathing and recovery periods.

Statement on ethical issues

Research involving people and/or animals is in full compliance with current national and international ethical standards.

Conflict of interest

None declared.

Author contributions

The authors read the ICMJE criteria for authorship and approved the final manuscript.

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