New Approaches to Marking Stages of Incremental Physical Work by Example of Cardiopulmonary Exercise Testing

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Abstract: The present study aims to divide physiological stages of involving physiological compensatory reactions in organs and systems which provide transport and consumption of O₂ during incremental physical exercise in healthy adults. Twenty seven untrained healthy volunteers, 19 men, mean age 25.0 ± 8.7 (18-28 years), BMI (body mass index) 26 ± 2.8 (19.0-27.3 kg/height, m²) and 18 triathletes, 10 men, mean age 22.3 ± 3.2 (17-25 years), BMI 21.4 ± 2.1 (19.8-23.4 kg/height, m²) were evaluated during progressive treadmill exercise test. CPET (cardiopulmonary exercise testing) was performed on treadmill with gas exchange system "Oxycon Pro" (Jaeger, Germany). Individual incremental exercise test protocol (ramp protocol) was created for every participant. All persons reached peak exercise in 12-15 minutes. Everybody was instructed to perform maximal exercise. Maximal exercise has been defined by a plateau of VO₂ (absence of increase VO₂ during incremental work rate), achievement RER 1.2 or maximal predicted HR (heart rate). The cubital venous catheter was installed in all subjects before exercise test. Blood samples were taken at baseline and at 1-minute intervals during test. pH, lactate and HCO₃⁻ concentration were estimated using analyzer i-STAT, cartridge CG4 (Abbot, USA). Physiological stages of involving compensatory reactions were determined by changes in pH, lactate and HCO₃⁻ levels in correlation with dynamics of VO₂ (oxygen uptake), VCO₂ (carbon dioxide output), V_E (minute ventilation), V_E/VCO₂ (ventilatory equivalent of carbon dioxide), RER (respiratory exchange ratio). RCP (respiratory compensation point) was determined, when ventilation dramatically increase relative to carbon dioxide output. Maximal work rate of athletes was reliably higher than of untrained healthy volunteers due to high level of training. Through first 3-5 min lactate concentration in blood was 2.1 ± 0.2 (1.9-2.5) Mm/L. It starts to increase when intensity of physical exercise reaches 12%-30% VO₂ peak and comes up to 12 ± 3.2 Mm/L (8-19 Mm/L) on exercise peak. Significant inflection of lactate concentration curve can be fixed on this stage and after this lactate concentration increases gradually. pH and HCO₃⁻ values were in normal limits at baseline: pH 7.32 ± 0.05, HCO₃⁻ 27.3 ± 2.1 Mm/L. pH does not change significantly till the intensity of exercise ≥ 45% of VO₂ peak and after this begins to diminish, that marks start of metabolic acidosis development. In all examined persons, this phenomenon appears significantly later than the increase of lactate concentration. Plateau of VO₂ appears at exercise intensity 93 ± 2.5% VO₂ peak. Entry of exercise in stage of plateau means that either cardiovascular and pulmonary systems, provide delivery of O₂ as utilization O₂ in muscles achieve its maximal capacities and increase of aerobic energy production is impossible further. Thus, we have marked four physiological stages during incremental physical exercise: lactate threshold, pH-threshold, respiratory compensation point and aerobic limit.

Key words: Physical work capacity, cardiopulmonary exercise testing, physiological stages of physical exercise.

1. Introduction

CPET (cardiopulmonary exercise testing) is a

standard method for estimation of O₂ consumption during physical work [1, 2] in the course of last decades [2-5]. Dynamics of O₂ consumption during exercise is usually attributed to heart rate. We propose to correlate it with alternation of energy costs compensation mechanisms for more precise

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description of physiological changes.

Our study is to divide physiological stages of involving physiological compensatory reactions in organs and systems which provide transport and consumption of O_2 during incremental physical exercise in healthy adults.

2. Materials and Methods

2.1 Ethics

All participants sign the inform content form approved by Ethical Committee of Federal Heart, Blood and Endocrinology Centre named after V.A. Almazov.

2.2 Participants

Twenty seven untrained healthy volunteers, 19 men, mean age 25.0 ± 8.7 (18-28 years), BMI 26 ± 2.8 ($19.0\text{-}27.3$ kg/height, m^2) and 18 triathletes, 10 men, mean age 22.3 ± 3.2 (17-25 years), BMI 21.4 ± 2.1 ($19.8\text{-}23.4$ kg/height, m^2) were evaluated during progressive treadmill exercise test.

During clinical and laboratory examination of participants were not revealed any disorders or diseases of cardiovascular, pulmonary and muscle systems, that can influence the CPET results. Spirometry and determination of hemoglobin level were performed to all participants purposely to exclude anaemia and pulmonary system pathology. Hemoglobin level ($121.4\text{-}150.6$ g/L) and spirometry measurements were corresponded to normal values.

2.3 Exercise Test

CPET was performed on treadmill with gas exchange system "Oxycon Pro" (Jaeger, Germany). Individual incremental exercise test protocol (ramp protocol) was created for every participant. All persons reached peak exercise in 12-15 min. Everybody was instructed to perform maximal exercise. Maximal exercise has been defined by a plateau of VO_2 (absence of increase VO_2 during incremental work rate), achievement RER 1.2 or maximal predicted HR (heart rate) [1].

2.4 Biochemical Analyses

The cubital venous catheter was installed in all subjects before exercise test. Blood samples were taken at baseline and at 1-min intervals during test. pH, lactate and HCO_3^- concentration were estimated using analyzer i-STAT, cartridge CG4 (Abbot, USA).

Physiological stages of involving compensatory reactions were determined by changes in pH, lactate and HCO_3^- levels in correlation with dynamics of VO_2 (oxygen uptake), VCO_2 (carbon dioxide output), V_E (minute ventilation), V_E/VCO_2 (ventilatory equivalent of carbon dioxide), RER (respiratory exchange ratio). RCP (respiratory compensation point) was determined, when ventilation dramatically increase relative to carbon dioxide output.

2.5 Statistical Analysis

The statistical analyses were performed with the use of the Statistika/PC (version 6.0, Windows). Continuous variables are expressed as the mean $\pm$ SD (standard deviation). Comparison of means of sample was performed using *T*-test. Differences were considered significant at *P*-value < 0.05 .

3. Results

CPET results are presented in Table 1.

Maximal work rate of athletes was reliably higher than of untrained healthy volunteers due to high level of training. It also confirmed by strongly marked increase of O_2 -pulse and less increase of heart rate during incremental exercise test, that means greater increase of stroke volume and higher arterial-venous O_2 difference. In spite of these differences, the same physiological stages of involving compensatory reactions in organs and systems which provide transport and consumption of O_2 were observed in both groups.

Dynamics of lactate concentration during physical exercise is presented in the Fig. 1. Through first 3-5 min lactate concentration in blood was 2.1 ± 0.2 ($1.9\text{-}2.5$) Mm/L. It starts to increase when intensity of

Table 1 Exercise test values of athletes and untrained healthy volunteers at peak exercise.

Group	Untrained healthy volunteers	Athletes	P
Measurements			
VO ₂	28 ± 5	62 ± 5 (48-78)	< 0.001
V _E /VCO ₂	26 ± 4 (22-33)	30 ± 3 (19-32)	< 0.001
Maximal work rate, watts	170 ± 10	250 ± 25	< 0.001
V _E	57 ± 5 (45-88)	125 ± 12 (90-178)	< 0.001
O ₂ /HR, mL	18 ± 1.8	25 ± 2.7	< 0.001

VO₂—oxygen consumption per 1 kg of weight, V_E—minute ventilation, V_E/VCO₂—ventilatory equivalent of carbon dioxide, O₂/HR—“oxygen pulse”.

Fig. 1 Dynamics of lactate concentration in venous blood of athlete during physical exercise.

Axis X—intensity of physical exercise expressed in percents of maximal oxygen uptake (VO₂ max).

Axis Y—lactate concentration in venous blood in Mm/L.

physical exercise reaches 12%-30% VO₂ peak and comes up to 12 ± 3.2 Mm/L (8-19 Mm/L) on exercise peak. Strongly marked increase of lactate concentration in venous blood means that muscular production of lactate exceeds peripheral consumption of lactate, and it is observed by intensity of physical exercise 12%-30 % VO₂ peak. Significant inflection of lactate concentration curve can be fixed on this stage and after this lactate concentration increases gradually. Such type of dynamics is observed at 42 participants (93%) of research group.

PH and HCO₃⁻ values were in normal limits at baseline: pH 7.32 ± 0.05, HCO₃⁻ 27.3 ± 2.1 Mm/L. pH does not change significantly till the intensity of exercise ≥ 45% of VO₂ peak and after this begins to diminish, that marks start of metabolic acidosis development. In all examined persons this phenomenon appears significantly later, than increase

of lactate concentration (Fig. 2). Delay of decrease pH in relation to increase of lactate concentration is probably caused by hemoglobin buffer system, which provides 75% buffer capacity of blood [6, 7]. Simultaneously, in period between points 1 and 2 (Fig. 2) bicarbonate concentration in blood is diminished, but pH decrease is not observed.

Evidently, that strongly marked increase of lactate concentration in blood leads to growth of carbon dioxide output, minute ventilation, respiratory exchange ratio. Figs. 3 and 4 demonstrate pattern of VO₂ (oxygen uptake), VCO₂ (carbon dioxide output), V_E (minute ventilation), V_E/VCO₂ (ventilatory equivalent of carbon dioxide), RER (respiratory exchange ratio), RCP (respiratory compensation point) during exercise. These changes take place as compensatory reactions owing to homeostasis disorders.

Intensity of physical exercise expressed in percents of maximal oxygen uptake (VO₂max)

Fig. 2 Dynamics of lactate concentration, pH and bicarbonate concentration in venous blood of athlete(woman) during incremental physical exercise.

Axis X—intensity of physical exercise expressed in percents of maximal oxygen uptake (VO₂ max).

Fig. 3 Dynamics of VO_2 , VCO_2 , V_E , V_E/VCO_2 , RER and RCP.

Axis X—intensity of physical exercise expressed in percents of maximal oxygen uptake (VO_2 max).

Point 1—Lactate threshold.

Point 2—Inflections of curves VCO_2 and V_E that reflects the development of metabolic acidosis—pH-threshold.

Point 3—Respiratory compensation point.

Point 4— VO_2 -plateau means that the maximum rate of oxygen consumption is reached and further increase of aerobic energy production is impossible.

Fig. 4. Changes of gas exchange measurements during increasing physical exercise and development of metabolic acidosis.

Axis X—intensity of physical exercise expressed in percents of maximal oxygen uptake (VO_2 max).

Point 1—Lactate threshold.

Point 2—pH Threshold.

Continuation of exercise provokes further increase of lactate concentration and decrease of pH, so metabolic disorders are aggravated (Fig. 4). For its compensation significant increase of minute ventilation is required and therefore hyperventilation is provoked, i.e., VCO_2 and ventilatory equivalent of CO_2 significantly increase.

In spite of described changes and continuous increase of work rate, oxygen consumption, up to a certain point, increases linearly and become stable (Fig. 4). VO_2 -plateau appears at exercise intensity $93 \pm 2.5\%$ of VO_2 -peak and means that the maximum rate of oxygen consumption is reached and further increase of aerobic energy production is impossible. Further energy production is possible due to anaerobic metabolism.

4. Discussion

We propose to divide incremental physical exercise into four physiological stages according to all CPET

data and dynamics of principals energy metabolism markers—pH, lactate and bicarbonate concentration in blood (Fig. 4).

Strongly marked increase of lactate concentration is observed by intensity of physical exercise 12%-30 % of VO_2 peak. We propose to call this point lactate threshold.

Second physiological stage is determined in point 2, which indicate the beginning of venous blood pH decrease. We propose to mark this stage as pH-threshold. Decrease of pH on this stage leads to stimulation of respiratory center and therefore to increase of minute ventilation, that correspond with inflections of curves VCO_2 and V_E .

Third physiological stage—respiratory compensation point—a condition in which the ventilation dramatically increases relative to CO_2 .

Fourth physiological stage corresponds to culmination of aerobic metabolism, after this increase of aerobic energy production is impossible. This stage can be called aerobic limit. Realization of incremental physical exercise after this stage is possible owing to increase of anaerobic energy production.

5. Conclusions

We have marked four physiological stages of energy costs compensation during incremental physical exercise in athletes and untrained healthy volunteers:

lactate threshold, pH-threshold, respiratory compensation point and aerobic limit.

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