

Express control of aerobic and anaerobic metabolism of athletes in cyclic sports events

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Abstract

Purpose: To develop express diagnostics of aerobic and anaerobic performance of athletes based on the electrocardiographic diagnostic method. **Material & Methods:** The athletes (candidates for master of sports and masters of sports) specialized in cycling (68 persons), rowing (76 persons), and speed skating (88 persons) were examined. The oxygen transport system, aerobic and anaerobic bioenergetics, and maximal accumulation of lactic acid in blood during the ergometric stress test and the recovery period were assessed. Prior to testing, electrocardiogram recording was performed in six thoracic unipolar Wilson leads, including V_{2R} , in the relative muscle resting state. The values of the percentage ratio of the amplitude of R wave to the sum of R and S in the leads from V_{3R} , V_1 and V_2 to V_4 , V_5 , and V_6 were compared to the indices of the oxygen transport system, aerobic and anaerobic bioenergetics, general physical work capacity, and maximum blood lactate concentration after completion of ergometry (3rd minute). The ergometric study used a continuous series of incremental step loads to failure, lasting two minutes each. The studies were conducted from 2010 to 2018. **Results:** The sum of the percentage ratios of the R wave amplitude to R+S in the right thoracic leads of the electrocardiogram (taken in V_{3R} , V_1 , and V_2 at relative resting muscle state) reflects the *maximum anaerobic (glycolytic) capacity of energy metabolism* (ANAME). The sum of the percentage ratios of the R wave amplitude to R+S in the left thoracic leads V_4 , V_5 , and V_6 reflects the *maximum capacity and power of aerobic metabolism* (MANAME). The electrocardiogram (recorded at rest) allows adequate assessing the aerobic and anaerobic components of muscle work capacity without the use of exercise tests. Minor time expenses for collection, processing, and analysis of the information obtained by electrocardiogram, as well as the possibility of practically unlimited repeatability of the study are the basis of monitorability of this method of *energy metabolism* assessment for operative and current control of training and competitive loads. **Conclusions:** The use of the electrocardiographic method for express diagnostics of aerobic and anaerobic performance allowed (for instance, in difficult conditions of the World Championship) providing the coaches with operative information about the “physiological cost” of each stage of this multiday competition and recovery period in the days of rest according to the state of aerobic and anaerobic metabolism of each member of the Ukrainian national team. Bioenergetic monitoring (provided by the described method of express diagnostics) permits developing and using target training regimes, determining the adaptation phases in the post-work period, objectively evaluating the efficiency of various methods and means of work capacity recovery. The operative assessment of training exercise “physiological cost” and account for the interaction of the occurring acute effect of each of them serve as the basis for choosing a rational sequence of their performance in a separate training session. The results of the conducted study were not influenced by the level of the athlete's motivation. Accessibility of the suggested method is determined by the fact that in addition to the tonometer for measuring blood pressure, single-channel portable electrocardiographs are the most common diagnostic device in medical control.

Keywords: cyclists, rowers, speed skaters, express method, electrocardiography.

Introduction

Since the metabolic basis of the manifestations of the main human motor qualities became known, the interest in studying the bioenergetics of muscular activity of different orientations, volumes, and intensities has sharply increased (Brosnan et al., 2014; Drezner et al., 2013). At the present stage, this problem has become particularly important for the practice of medical and pedagogical observations in elite sports (Alvares-Romero et al., 2021). Analysis of tendencies of functional diagnostics development indicates the increasing relevance of muscular activity bioenergetics due to the steady expansion of applying a complex of various means and methods for stimulation of work capacity and recovery processes at all stages of athletes' preparation for the highest achievements (Chandra et al., 2012; Merone et al., 2016; Sharma et al., 2017).

In medical and physiological control the study of the efficiency of these means and methods rests upon quantitative assessment of size and direction of stimulation-induced shifts of the basic parameters, which characterize a state of aerobic and anaerobic energy metabolism (Sheikh et al., 2014). Such type of control is optimal only when using diagnostic methods authentic according to validity, reliability, and objectivity criteria and when there is a sufficiently effective system of collecting, processing, analyzing, and obtaining information on a real time basis (Weiner et al., 2011). However, it is the latter that remains the least developed in the system of evaluating acute and delayed training effect in athletes. This is largely due to the fact that modern concepts in the theory and methodology of operative control for the functional state of organs and systems that provide muscle work capacity are based on the use of tests with a physical load of submaximal or maximum power (Corrado et al., 2010; Koch et al., 2012). However, their non-specificity, inconvenience, trace reactions, blood sampling, and low motivation (especially in more skilled athletes) significantly devalue the hard-earned data (Harmon et al., 2015).

Known time expenditures for organizing and conducting (especially in training and competitive conditions) studies of operative and current state of athletes according to indices of aerobic and anaerobic metabolism are best characterized by the lack of monitorability of almost all methods used in medical and physiological control. This quality is of fundamental importance for the daily practice of training process management (Corrado et al., 2010; Pelliccia et al., 2012).

The search for radically new ways of determining the main energy metabolism parameters can become a constructive basis for the elaboration of an express diagnostic system. One of such ways is based on previously unknown biological regularity, which was revealed by S.A. Dushanin (1985) during medical and pedagogical observations of members of Ukrainian national teams in cyclic sports events.

While analyzing and generalizing the complex of numerous data obtained in the course of these observations on the structure of athletes' functional fitness and efficiency of their competitive activity, it was proved that the kinetics of energy supply of sodium "pump" activity at the cellular level in the human myocardium (being at relative rest) corresponds in orientation to the energy production during a muscular activity of the whole body.

A comparative study of 236 athletes using multistep correlation, regression, and factor analysis revealed close conjugation between myocardial cell membrane permeability (sodium ion "channel"), the rate of transmembrane action potential increase during ventricular depolarization (sodium migration rate into the cell), recorded in a relative resting muscle state, and the values of aerobic and anaerobic metabolism of muscular activity of any orientation, volume, and intensity.

J.A. Drezner et al. (2013) in his studies compared the transmembrane action potential curve of an individual myocardial cell, recorded by means of microelectrode technique, with the electrocardiogram recorded from the body surface. It has been proved that in terms of the degree of occurring differentiation, the electrocardiogram represents the curve of the rate of change of the potential difference registered during transmembrane recording, i.e., the first derivative of the electrocardiogram. If the amplitude of R wave in electrocardiogram is referred to as the sum of R and S amplitudes, then the relative value of such ratio expressed as a percentage ($R-100/R+S$) will indirectly reflect the state of the ion "channel" of myocardial cell membrane for sodium in such parameter as the speed of its input flow into the cell during zero phase of action current (Dushanin, 1985; Riding et al., 2015). This served as the idea for the present studies.

Objective – to develop express diagnostics of aerobic and anaerobic performance of athletes based on the electrocardiographic diagnostic method.

Materials & Methods

Participants. The athletes (candidates for master of sports and masters of sports) specialized in cycling (68 persons), rowing (76 persons), and speed skating (88 persons) were examined.

Organization of studies. The oxygen transport system, aerobic and anaerobic bioenergetics, and maximal accumulation of lactic acid in blood during the ergometric stress test and the recovery period were assessed. Before testing, electrocardiogram recording was performed in six thoracic unipolar Wilson leads, including V_{2R} , in the relative muscle resting state. The values of the percentage ratio of the amplitude of R wave to the sum of R and S in the leads from V_{3R} , V_1 and V_2 to V_4 , V_5 , and V_6 were compared to the indices of the oxygen transport system, aerobic and anaerobic bioenergetics, general physical work capacity, and maximum blood lactate concentration after completion of ergometry (3rd minute). The ergometric study used a continuous series of incremental step loads to failure, lasting two minutes each. Their individualization was made according to the recommendations of the International Committee on Standardization of Physical Fitness Tests (Uberti et al., 2011). The aerobic oxidative capacity reserve was determined by the maximum oxygen consumption (VO_{2max}) measured during the stress test. Anaerobic contribution (in kJ and kJ per kg of body weight) at each load stage during bicycle ergometry was assessed by gasometric method without measuring oxygen debt according to the method of S.A. Dushanin (1985). Blood lactic acid was determined according to Strom's modification of Barker-Summerson technique at the 3rd and 5th minutes of the recovery period. The state of metabolic systems of aerobic and anaerobic energy production during the supramaximal ergometric test was assessed according to the

criteria of power, capacity, efficiency, reactivity and stability (Gtowacka et al., 2012; Reineck et al., 2013; Spence et al., 2011).

Statistical analysis. The findings were subjected to mathematical processing. The following statistical parameters of the sample were calculated; arithmetic mean (X); standard deviation (S); coefficient of variation (V%); ΔX - confidence interval corresponded to 95%. Student's t-test was used to compare the two normal distributions. The critical level of significance in testing statistical hypotheses was $p < 0.05$. Correlation analysis of the obtained results was performed using the linear Pearson correlation coefficient.

The study was conducted in compliance with the ethical principles of the European Convention and the Helsinki Declaration (ethics principles regarding human experimentation). It was confirmed by the Bioethics Commission of the University. Examined provided written approvals for analysis and subsequent disclosure.

Results & Discussion

Comparisons of the data obtained in the studied groups of athletes allowed establishing fundamentally new regularities.

Along with the enhancement of aerobic oxidative capacity reserve (verified according to VO_{2max} in absolute and relative units), a statistically significant increase in the sum of the ratios of R to R+S wave amplitudes in the left thoracic leads V_4 , V_5 , and V_6 of the electrocardiogram (recorded at relative resting muscle state) is noted. Its increase in the second group of athletes (VO_{2max} from 3.1 to 4.0 $l \cdot min^{-1}$) compared with the first group (VO_{2max} 3.0 $l \cdot min^{-1}$ or less) averaged 12% (Table 1). In the third group of athletes compared to the second group, the increase constituted 10%. In athletes with VO_{2max} 5.0 over $l \cdot min^{-1}$ it reached 11% ($p < 0.01$). Simultaneously, the oxygen effect of cardiac contraction increased significantly. This was objectified by the corresponding elevation of maximal oxygen pulse.

Table 1. Dynamics of indices of bioenergetics, physical work capacity, and ECG in athletes depending on the aerobic oxidative capacity reserve

Indices	aerobic oxidative capacity reserve, $l \cdot min^{-1}$			
	3.0 <	3.01-4.0	4.01-5.0	5.0 >
Maximal oxygen consumption, $l \cdot min^{-1}$	2763.6±58.8	3631.9±46.5	4355.4±46.8	5631.8±49.9
Maximal oxygen consumption, $ml \cdot min \cdot kg^{-1}$	38.6±0.99	46.7±1.2	52.5±1.4	60.8±2.2
Load volume, kJ	182.9±15.2	222.8±8.6	259.8±11.9	297.2±16.8
PWC _{max} , kJ	16.9±0.5	20.8±0.64	22.8±0.73	25.7±0.9
PWC _{max} , $J \cdot kg^{-1}$	233.4±3.9	254.8±4.3	269.0±5.2	279.4±5.2
max.O ₂ – HR, $ml \cdot beats^{-1}$	11.97±0.65	17.96±0.32	21.8±0.49	28.6±1.96
Resting ECG, V_4-V_6 , %	203.4±6.5	229.7±5.6	251.6±4.8	279.8±8.4
Resting ECG, $V_{3R}-V_2$, %	78.2±6.2	81.4±5.6	86.3±5.8	83.8±6.8

A high degree of correlation between the actual VO_{2max} value and the sum of R to R+S percentage ratios in the left thoracic electrocardiogram leads (at rest) was confirmed by the fact that the correlation coefficient reached 0.831 at $p < 0.0005$ (Fig. 1).

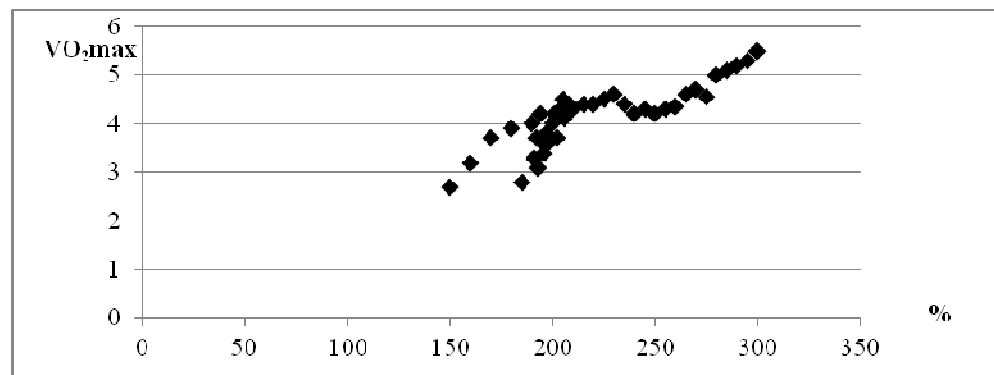


Fig. 1. Correlation dependence between maximal oxygen consumption ($l \cdot min^{-1}$) and the total value of percentage ratios of R-100 to R+S wave amplitudes in left thoracic leads V_4 , V_5 , V_6 (%) at rest

The dynamics of the sum of the percentages of these electrocardiogram amplitude characteristics in the right thoracic leads V_{3R} , V_1 , and V_2 did not conjugate with VO_{2max} changes in the examined athletes. Correlation analysis confirmed this regularity. It turned out that there was no correlation between these parameters ($r = 0.012$).

The distribution of the examined athletes according to the value of another, no less important parameter of aerobic energy, capacity, also permitted to state the unidirectional changes in the maximum aerobic metabolic capacity (MAMC) and the total value of the percentage ratios of R to R+S in the left thoracic unipolar leads of the electrocardiogram at rest (Table 2).

Table 2. Dynamics of the indices of bioenergetics, physical work capacity, and ECG in athletes depending on the aerobic metabolic capacity reserve

Indices	Maximal aerobic metabolic capacity, kJ		
	418.4 <	418.5-627.6	627.7 >
MAMC, kJ	337.2±10.0	521.3±8.2	710.9±21.0
MAMC, kJ.kg ⁻¹	4.6±1.9	6.4±1.6	8.8±0.46
Load volume, kJ	191.6±9.4	139.2±8.1	299.3±11.7
PWC _{max} , kJ	17.8±0.86	259.8±4.08	23.3±1.03
PWC _{max} , J.kg ⁻¹	237.0±7.8	251.3±8.4	286.2±9.0
max.O ₂ – HR, ml.beats ⁻¹	17.1±1.36	19.8±0.51	25.1±1.80
ECG at rest, V ₄ -V ₆ , %	203.6±6.3	238.4±4.5	256.7±5.1
ECG at rest, V _{3R} -V ₂ , %	82.1±6.8	86.3±4.5	77.4±4.6

The greater the transmembrane action potential at the zero phase of left ventricular myocardial depolarization on resting electrocardiogram (which is registered in leads V₄, V₅, and V₆), the higher the aerobic capacity of strenuous muscular activity energy supply. The results of the correlation analysis showed an even closer correlation between them compared to VO_{2max}. The correlation coefficient reached 0.902. At the same time, no correlation between the changes of maximal aerobic metabolic capacity and the total value of the percentage ratios of R to R+S wave amplitudes in the right thoracic unipolar leads V_{3R}, V₁ and V₂ on the electrocardiogram at rest was observed (Kolumbet et al., 2019).

The revealed during comparative assessment conjugation between the maximum values of lactic acid accumulation in blood after supramaximal in power and long-term loads of cyclic character and the transmembrane action potential in the zero phase of right ventricular myocardial depolarization on resting electrocardiogram, recorded in thoracic leads V_{3R}, V₁, and V₂ becomes of fundamental importance (Table 3).

Table 3. Dynamics of the indices of bioenergetics, physical work capacity, and ECG in athletes depending on blood lactate maximal accumulation

Indices	Blood lactic acid, mmol.l ⁻¹		
	7.8 <	7.81-10.0	10.1 >
Blood lactate, mmol.l ⁻¹	5.96±0.32	8.50±0.16	12.2±0.51
MANAME, kJ	118.8±6.7	112.5±8.5	118.4±10.3
MANAME, kJ.kg ⁻¹	1.60±0.14	1.50±0.08	1.38±0.09
Volume load, kJ	172.9±13.5	221.7±13.1	243.0±22.2
PWC _{max} , kJ	18.8±0.57	17.8±0.83	19.5±1.30
PWC _{max} , J.kg ⁻¹	240±24	234±7	231±8
ANAME, kJ	431.4±34.8	569.7±50.6	671.9±70.7
ANAME, kJ.kg ⁻¹	5.4±0.37	7.57±	
ECG at rest, V ₄ -V ₆ , %	76.9±4.2	81.6±6.2	97.8±4.5
ECG at rest, V _{3R} -V ₂ , %	222.9±12.6	206.4±8.8	224.8±7.04

Legend: MANAME – maximal power of anaerobic metabolism; ANAME – maximal anaerobic metabolic capacity

As the range of maximum blood lactate fluctuation increased, a significant ($p<0.01-0.05$) increase in the sum of percentage ratios of R to R+S wave amplitudes in V_{3R}, V₁ and V₂ leads on electrocardiogram (recorded at relative resting muscle state) was observed. A high degree of correlation between them was confirmed by the fact that the correlation coefficient constituted 0.833 at $p<0.001$ (Fig. 2).

At the same time, no relationship between the changes in the sum of the percentage ratios of R wave to R+S wave amplitudes in the left thoracic resting electrocardiogram leads and the limits of the maximum blood lactate fluctuations during the recovery period was revealed (Table 3). The correlation coefficient between them reached only 0.182 at $p>0.05$.

The sum of the percentage ratios of the R wave amplitude to R+S in the right thoracic leads of the electrocardiogram (taken in V_{3R}, V₁ and V₂ at relative resting muscle state) reflects the *maximum anaerobic (glycolytic) capacity of energy metabolism* (ANAME). The sum of the percentage ratios of R wave amplitude to R+S in the left thoracic leads V₄, V₅, and V₆ reflects the *maximum capacity and power of aerobic metabolism* (MANAME).

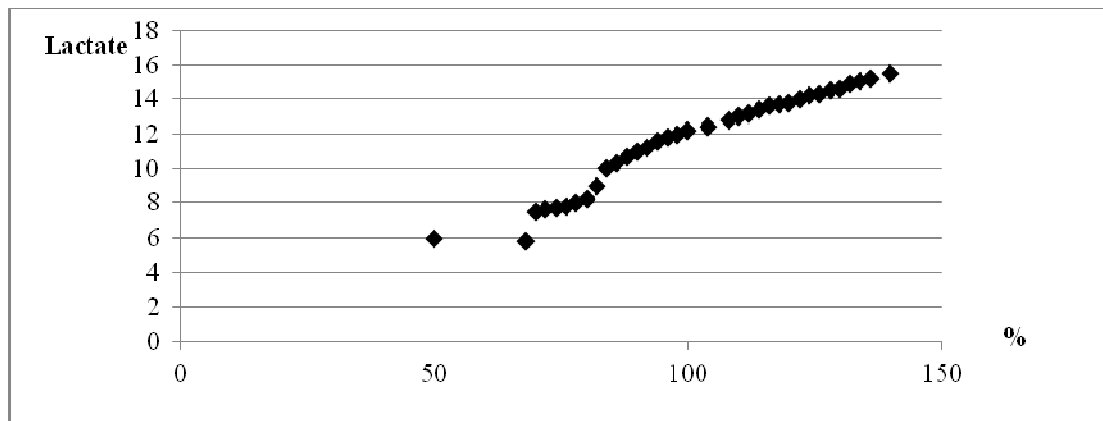


Fig. 2. Correlation dependence between maximum blood lactate accumulation after stress test with physical load (lactate, mmol.l⁻¹) and the total value of percentage ratios of R•100 to R+S wave amplitudes in right thoracic leads V_{3R} and V₂ (%) on the electrocardiogram at rest

This means that the electrocardiogram (recorded at rest) may permit to adequately assess the aerobic and anaerobic components of muscle work capacity without the use of tests with a physical load. Insignificant time expenditures for collection, processing, and analysis of information provided by electrocardiogram, as well as the possibility of practically unlimited repeatability of the study are the basis for monitorability of this method of *energy metabolism* assessment for operative and current control of training and competitive loads. This is best confirmed by the data presented in Figure 3.

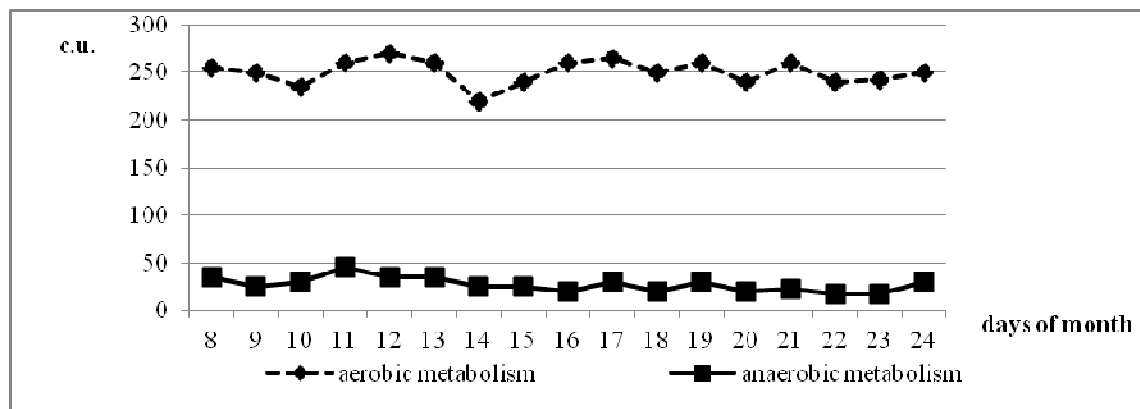


Fig. 3. Metabolic profile (energy metabolism, c.u.) of one of the members of the Ukrainian national team at the World Championship according to data of bioenergetic monitoring within month of preparation

Conclusions

The application of the electrocardiographic method for express diagnostics of aerobic and anaerobic performance allowed (for instance, in difficult conditions of the World Championship) to provide coaches with operative information about the “physiological cost” of each stage of this multi-day competition and recovery period during rest days according to the state of aerobic and anaerobic metabolism of each member of the Ukrainian national team.

Bioenergetic monitoring (which is provided by the described method of express diagnostics) allows developing and using target training regimes, determining adaptation phases in the post-work period, objectively evaluating the efficiency of various methods and means of work capacity recovery.

Operative assessment of the “physiological cost” of training exercises and account for the interaction of the occurring acute effect of each of them serve as the basis for choosing a rational sequence of their performance in a separate training session. The results of the conducted study were not influenced by the level of the athlete’s motivation. Accessibility of the suggested method is determined by the fact that in addition to the tonometer for measuring blood pressure, single-channel portable electrocardiographs are the most common diagnostic device in medical control.

Conflict of interest

The authors declare that there is no conflict of interests.

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