

Ventricular Repolarization of the Heart of Cross-Country Skiers at Different Stages of the Annual Training Cycle

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Received August 24, 2017

Abstract—The study of the heart electrical activity of cross-country skiers with a high sports qualification has been carried out at different stages of the annual training cycle. It has been found that the morphofunctional cardiac reconstructions associated with an increase in the intensity of physical workloads from the preparatory cycle to the competition stage lead to a change in the repolarization of the ventricles: the early repolarization duration of the ventricles (the $T_{peak}-T_{end_{II}}$ interval) was significantly decreased during the recovery from submaximal exercise on ECG_{II}; the negative extremum amplitude of the cardio electric field on the body surface of athletes increases significantly with an insignificant increase in the amplitude of the T wave on the ECG_{II}. The individual cardioelectropographic analysis of the cardio electric field on the body surface of the examined athletes during the period of ventricular repolarization showed a change in the amplitude–time dynamics of the extrema at the competition stage in comparison with the preparatory stage.

Keywords: heart electrical activity, ventricular repolarization of the heart, physical training macrocycle, cross-country skiers

DOI: 10.1134/S0362119718050134

Among the specific features of the training process of ski racers are cyclicity, alternation of the stages differing in intensity and the volume of physical activities and their interrelation, which increase overall, and special endurance of the body when preparing for the competitions [1]. A primary, preparatory stage of the annual training cycle is aimed at the formation of basic working capacity and competition form. The highest level of physical efficiency of an athlete essential for getting athletic performance is achieved at the main competitive stage. The macrocycle terminates with the transitional and recovery stages. Cross-country skiing belongs to cyclic sports with a characteristic motion pattern and multiple repetitions of identical movements that contributes to the development of, first of all, a physical characteristic, endurance [1, 2]. Strict requirements applicable to the athlete's body lead to functional rearrangements in all systems and organs and mostly affect the oxygen transport system. The following changes are indicated in ski racers after the preparatory stage: an increase or decrease in heart rate (HR); an increase in stroke and minute volumes; alteration in vascular resistance and regulation; an increase in the heart force and ejection fraction, etc. [3]. Structural and functional changes in the myocardium that result from many years of training, “physiological remodeling”, are accompanied by changes in the myocardium electrical activity, especially ventricular repolarization, since this process is the most sen-

sitive to the exposures of different genesis. During the transition to the competitive stage of preparation, on the ECG of ski racers the indices of partial bundle branch block become more prominent, T wave morphology changes, ST segment shifts relative to the isoline [4]. At the competitive stage, an increase in the repolarization abnormalities compared to the preparatory stages is observed in 64% athletes [5].

The sensitivity of the traditional ECG diagnosis used for the evaluation of the heart electrical activity in athletes in a resting state is significantly lower than that in the population of apparently healthy individuals and the study of an “athlete's heart” is reasonably to conduct only during the stress testing [6].

The goal of the present study was to investigate the myocardium electrical activity during the ventricular repolarization in ski racers at different stages of the annual training cycle under the conditions of stress testing.

METHODS

Highly qualified male cross-country ski racers ($n = 14$), including Candidates for Master of Sport, Masters of Sports of Russia, and Masters of Sports of Russia of International Class, at the preparatory (PS, August) and competition (CS, February–March) stages of the annual training cycle were invited for the

Table 1. ECG_{II} parameters in the athletes examined in a resting state and during the recovery period after submaximal FE

ECG _{II} parameters	Rest	PS		CS	
		1 min recovery	3 min recovery	1 min recovery	3 min recovery
<i>Q</i> amplitude, mV	-0.12 ± 0.02	-0.04 ± 0.01	-0.04 ± 0.01	-0.34 ± 0.25*	-0.21 ± 0.1*
<i>Q</i> duration, ms	0.01 ± 0.00	0.01 ± 0.00	0.01 ± 0.01	0.02 ± 0.01*	0.02 ± 0.01*
<i>R</i> amplitude, mV	1.71 ± 0.13	1.52 ± 0.55	1.56 ± 0.42	2.58 ± 0.37*	3.62 ± 0.59*
<i>R</i> duration, ms	0.06 ± 0.01	0.04 ± 0.01	0.05 ± 0.01	0.03 ± 0.02	0.06 ± 0.02
<i>S</i> amplitude, mV	-0.81 ± 0.24	-1.17 ± 0.038	-0.60 ± 0.46	-0.57 ± 0.24	-0.60 ± 0.42
<i>S</i> duration, ms	0.03 ± 0.01	0.04 ± 0.01	0.04 ± 0.01	0.02 ± 0.01*	0.03 ± 0.01

* Statistically significant differences at the CS compared to the indices at the PS.

prospective study. The ski racers examined were 20 (19–28) years old with the body length of 175.5 (170.5–180.5) cm and body weight of 69.5 (64.0–74.5) kg. All participants received a detailed explanation of the goal of the study. An informed written consent for the participation in the experiment was obtained from each participant.

Heart electrical activity was recorded by the method of multichannel synchronous cardioelectrotopography in 64 unipolar chest leads synchronously with the standard limb leads in a seated position in a resting state and at the end of every minute of the 3-min recovery period (from the first to the third minutes) after submaximal physical exercise (FE). Stress testing was performed with a cycle ergometer using the standard *PWC*₁₇₀ test (cycle ergometer stress testing).

Cardioelectrotopography allows the evaluation of not only the amplitude and time characteristics of the myocardium electrical activity, but also spatial characteristics that significantly increases its diagnostic value [7]. However, in performing a physical task, it is recommended to mainly assess the amplitude and time extremum parameters, because a significant decrease in the QT interval and monophasic electric potential of the cardiomyocytes together with a acute HR increase during the load often lead to error in interpretation of spatial parameters of the cardioelectric field [8].

The analysis of the heart electrical activity included the following: evaluation of standard ECG_{II} characteristics in the second limb lead (amplitudes and durations of the Q, R, S, and T waves), determination of the durations of the J–Tpeak_{II} and Tpeak–Tend_{II} intervals and cardioelectric field (CEF). Cardiac electric potentials were recorded via 64 ECG leads placed on the torso surface using an automated multichannel apparatus; CEF was analyzed using the instantaneous equipotential maps which reflect the electrical activity of the heart at any given moment on a flat pattern of the body surface to the plane of rectangle the left side of which corresponds to the ventral area, and the right one, to the dorsal area of the body. The following parameters were assessed: the spatial location of the

zones and extrema of positive and negative cardiac electric potentials and the absolute amplitude of the cardiac potential extrema at each point in time with 0.25 ms signal sampling.

In the functional test to minimize artefacts produced by working skeletal muscle on the CEF, the cardiac electric potentials were recorded from the torso surface not immediately after the athlete's motion stops, but at the end of the first and the following minutes of recovery.

Statistical data processing was performed using the Statistica 10.0 software (StatSoft, United States). The normality of distribution was assessed using the Shapiro-Wilk test. Data with normal distribution were analyzed using parametric test for independent samples and paired sample test to compare the “before–after” differences. The results were presented as the mean ± standard deviation ($M \pm SD$). If the data distribution was not normal, the values were analyzed using Wilcoxon's test for dependent samples, and the results were presented as the median and quartiles ($Me (Q1; Q3)$). The differences between the samples were considered statistically significant at $p < 0.05$.

RESULTS

Comparative analysis of the ECG_{II} parameters in ski racers at the preparatory and competitive stages after FE compared to the rest state revealed significant differences in the amplitudes and durations of the waves of primary ventricular activity (Table 1).

The RR-interval duration in the skiers examined was 1.06 ± 0.19 , 0.53 ± 0.07 , 0.64 ± 0.08 , and 0.68 ± 0.08 s at the PS, and 0.95 ± 0.26 , 0.45 ± 0.05 , 0.60 ± 0.11 , and 0.65 ± 0.11 s at the CS at rest and on the first, second, and third minutes of recovery, respectively. The HR was 62 ± 5 , 85 ± 7 , 76 ± 4 , and 74 ± 4 bpm at the PS and 70 ± 10 , 90 ± 5 , 81 ± 7 , and 78 ± 7 bpm at the CS at rest and from the first to the third minutes of recovery, respectively. Statistically significant difference in RR-interval duration and HR between the stages in ski racers was observed on the first minute of rest after the load.

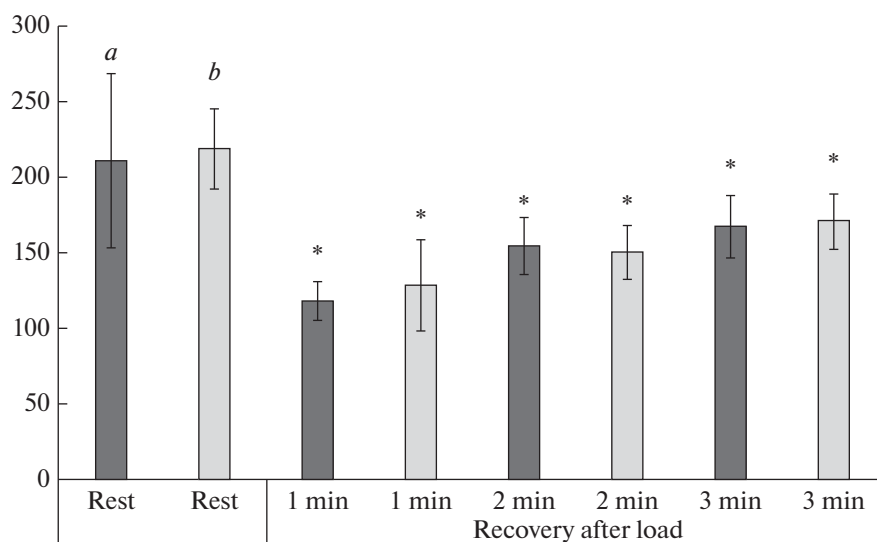


Fig. 1. The J–Tpeak_{II} interval duration in the athletes examined at different stages of the training cycle in a resting state and during the recovery period after submaximal workload. (a) The preparatory stage; (b) the competition stage; * statistically significant difference from the resting state.

No significant difference was observed in the QT_{II} interval duration in the athletes examined at different stages of the training cycle. The QT_{II} interval duration at the PS at rest was 411 ± 40 ms; in the recovery period, QT_{II} interval duration was significantly lower than in a resting state ($p < 0.05$), namely, 284 ± 23 , 321 ± 22 , and 344 ± 27 ms on the first, second, and third minutes, respectively. At the CS, the QT_{II} interval duration was also significantly lower than that at rest, namely, 399 ± 34 ms; and 275 ± 33 , 308 ± 32 , and 337 ± 22 ms on the first, second, and third minutes of rest after FE, respectively ($p < 0.05$).

The T_{II} wave amplitude in athletes at the PS at rest from the first to the third minutes of recovery after FE was 0.869 ± 0.117 , 1.196 ± 0.236 , 1.064 ± 0.238 , and 0.788 ± 0.128 mV, respectively. The T_{II} wave amplitude did not change significantly at the CS compared to the PS.

The J–Tpeak_{II} interval duration in the athletes examined at the PS at rest was 211.14 ± 58.2 ms; on the first, second, and third minutes of the recovery period after FE, it was 118.43 ± 12.58 , 154.57 ± 18.78 , and 167.71 ± 20.43 ms, respectively; and on every minute it was significantly lower than at rest ($p < 0.05$). The J–Tpeak_{II} interval duration at the CS did not change significantly compared to the PS (Fig. 1).

The Tpeak–Tend_{II} interval duration in athletes at the PS was 91.71 ± 13.50 , 74.0 ± 15.63 , 79.43 ± 7.74 , and 88.29 ± 11.09 ms in a resting state, and did not change significantly on the first, second, or third minutes of recovery. The Tpeak–Tend_{II} interval duration at the CS was significantly lower on the third minute of recovery (78.29 ± 4.75 ms) compared to the PS (Fig. 2).

The amplitude of the maximal negative CEF extremum during the ventricular repolarization period in the athletes examined in a resting state (0.47 ± 0.10 mV) and on the third minute of the recovery period (0.43 ± 0.09 mV) was significantly higher at the CS than the values at the PS (0.28 ± 0.09 mV and 0.30 ± 0.07 mV respectively) (Fig. 3).

The amplitudes of the maximal positive CEF extremum and the times of achieving maximum values by the positive and negative CEF extrema in the period of ventricular repolarization at different stages of the training cycle did not differ significantly.

In the context of changing the J–Tpeak_{II} interval duration and almost constant Tpeak–Tend_{II} interval duration in athletes in response to FE, we studied individual dynamics of the positive and negative extremum amplitudes during repolarization in a resting state during the recovery period after FE at different stages of the training cycle. Alteration in the extrema dynamics on the CEF on the body surface of the athletes in response to physical exercise has been observed; at the PS, there was a slight increase in the amplitudes of positive and negative CEF extrema and the achievement of their maximum values occurs earlier within the period of ventricular repolarization than in a resting state. At the CS, CEF extrema reached maximum amplitude earlier and the positive extremum had a greater amplitude.

For example, analysis of the CEF extremum dynamics in M.A. demonstrated that, at the PS, the positive and negative extrema reached their maximum values during the repolarization period on the descending T wave in ECG_{II} both at rest and after performing submaximal FE (Fig. 4).

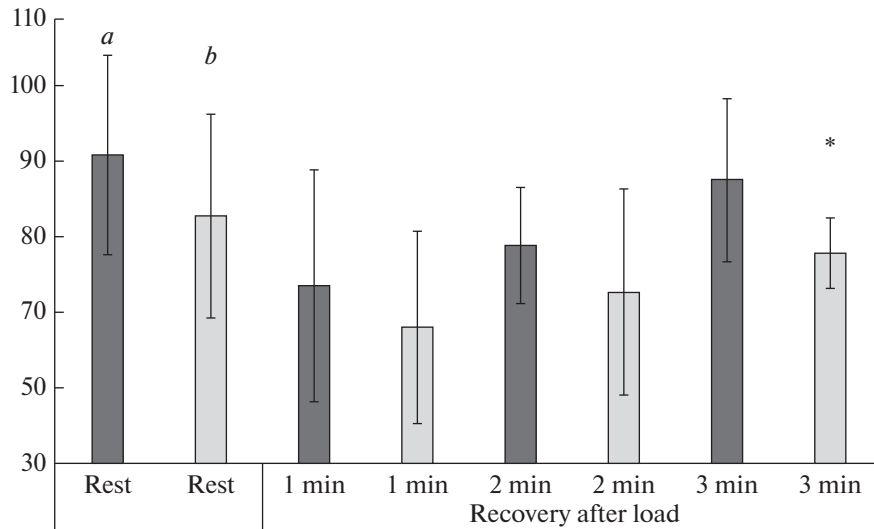


Fig. 2. The Tpeak–Tend_{II} interval duration in the athletes examined at different stages of the training cycle in a resting state and during the recovery period after submaximal load. * Statistically significant difference between the stages *a* and *b*. See Fig. 1 for designations.

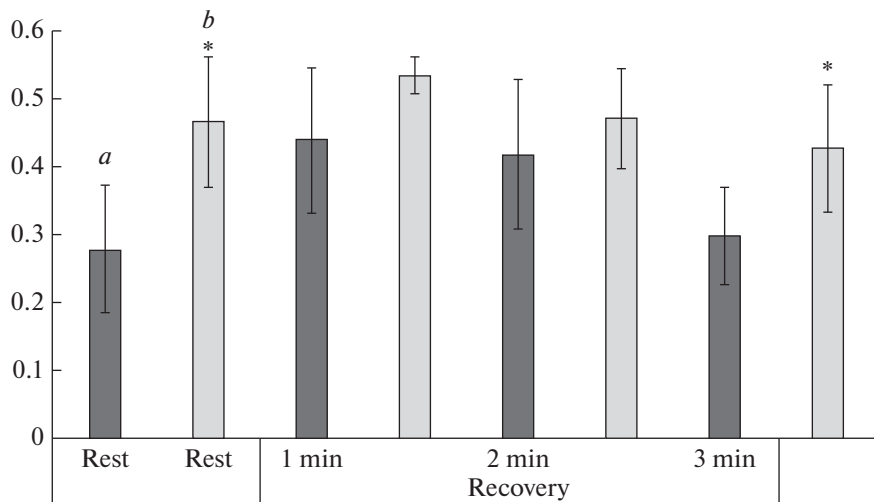


Fig. 3. The amplitude of the maximal negative CEF extremum during the ventricular repolarization period in the athletes examined in a resting state and during the recovery period after submaximal load. See Fig. 1 for designations.

At the CS, in M.A. examined, resting CEF extrema reached their maximum values during the descending T wave phase of the ECG_{II}, whereas after FE, the CEF extrema reached their maximum values within the ascending T wave phase. The J–Tpeak_{II} interval shortening in response to FE compared to the resting state was lower at the CS than at the PS.

Study of the heart electrical activity at rest and after load testing in athletes developing endurance at different stages of the training cycle revealed alteration of the proportion of extremum dynamics in the period of ventricular repolarization against the backdrop of an

almost unchanged T_{II} wave amplitude at different stages.

DISCUSSION

An increase in training level after the period of preparation to the competitive stage of the annual cycle in ski racers manifested itself by the development of bradycardia and lesser HR gain during the exercise performance [5].

At the PS, HR increase in response to workload was accompanied by an increase in stroke blood volume, whereas at the CS, the response of the blood cir-

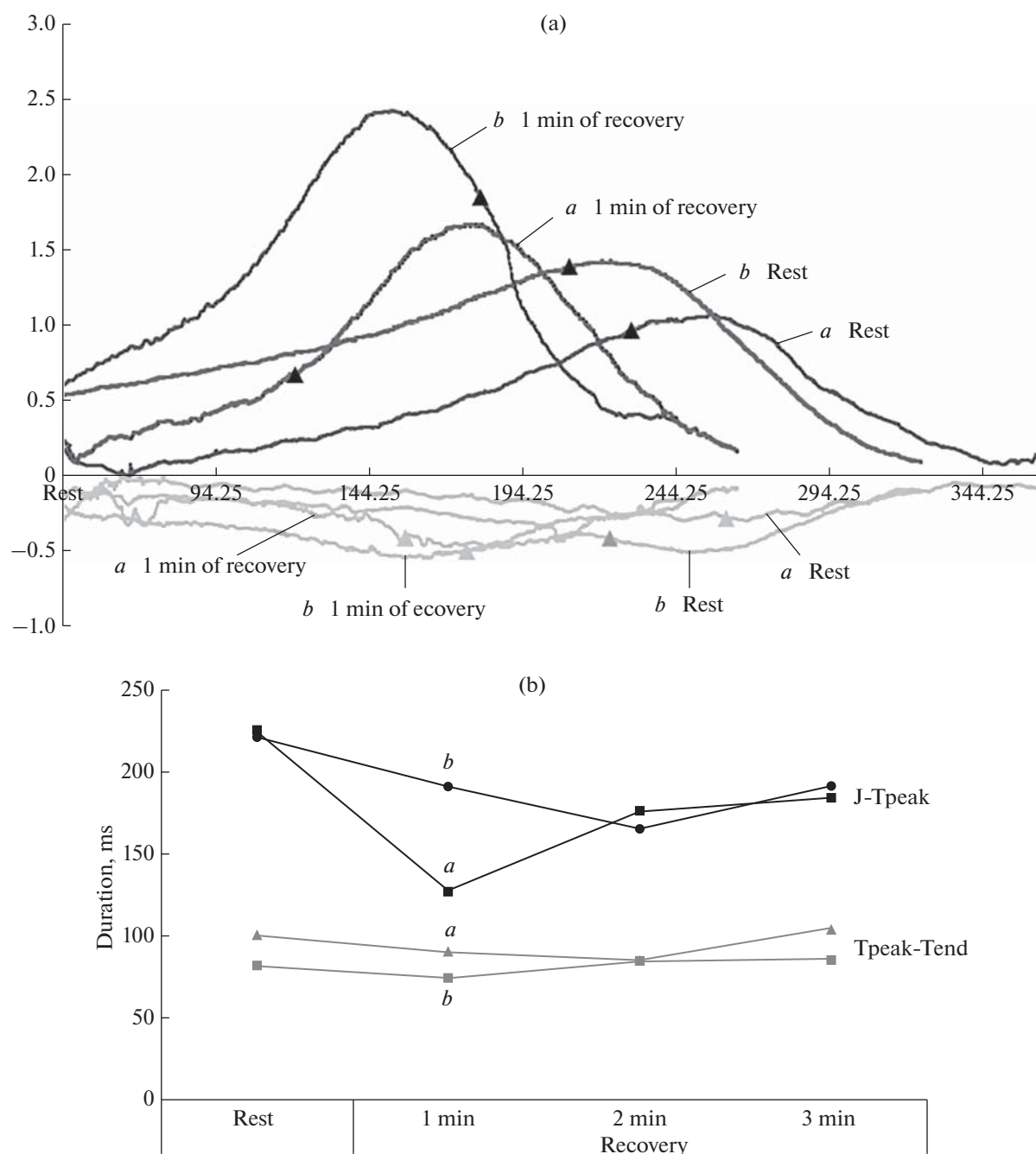


Fig. 4. Changes in the (a) amplitudes of positive and negative extrema and (b) the J-Tpeak_{II} and Tpeak-Tend_{II} intervals in M.A. in a resting state and during the recovery period after FE at different stages of the training cycle. Δ corresponds in time to the peak of the T wave on the ECG_{II}. See Fig. 1 for designations.

culatory system to exercise load occurs mainly because of HR increase without the rise of stroke volume [9, 10]. In the ski racers examined, HR in the initial state and during the period of recovery after FE was higher at the CS than at the PS, which indicated that the athletes were at the peak of their functional capabilities.

The following features were observed in the standard ECG of the athletes at the competition stage in compare with preparatory stage independently from

the specific of their athletic activity: the lack of significant shifts in QRS interval duration, an increase in T-wave durations, QT interval elongation at rest [11]. Change in the QT interval duration in response to physical exercise is one of the clinical criteria which characterize the risk of sudden cardiac death in sports. If this index is increased during FE, according to the International Recommendations for Electrocardiographic Interpretation in Athletes [12], an athlete

should be excluded from competition and sent to rehabilitation. In the ski racers examined in our experiment at the PS and CS, the QT interval duration after cycle ergometry was significantly lower than the initial duration at rest and fell within the ranges typical of an apparently healthy individual.

In the group of the subjects examined, no significant changes in the amplitude or duration of the T-wave in the ECG_{II} at rest and after FE were observed at different stages of the training cycle. However, a more detailed analysis of ventricular repolarization has demonstrated that physical exercise intensification resulted in a statistically significant alteration in the J–Tpeak_{II} (early repolarization period) duration after exposure to load testing, the Tpeak–Tend_{II} (late repolarization period) duration being almost constant.

The electrocardiographic amplitude and shape of the T wave consist of a combination of electric potentials of endo-, myo-, and epicardial cells during repolarization, which corresponds to peak, plateau, and descending phase on the monophasic action potential of each cardiomyocyte [13]. Repolarization initially occurs in the epicardial cells and forms an ascending arm of the T wave, whereas a thicker layer of myocardial cells which repolarize later contributes more to the formation of T wave than epi- and endocardial layers do. There is an opinion that repolarization of the epicardium terminates by the peak of the T wave in the ECG; i.e., it covers the first half of the repolarization period, the J–Tpeak interval, whereas repolarization of myocardium and endocardium, by the descending phase of the T wave and corresponds to the duration of the Tpeak–Tend interval in the second half of the period [14].

Alteration in the proportion of time and amplitude characteristics of CEF extrema, dynamics of the extremum increase, and time of reaching their maximum values when the shape and amplitude of the T wave in the ECG in the limb leads are almost constant are associated with the change in the heart function in ski racers resulting from a gradual increase in training intensification when preparing for competition.

In most athletes whose sports speciality implies the development of endurance (ski racers, swimmers, and runners), the electrical axis of the heart shifts to the right, in the developing strength athletes (weight-lifting), leftward displacement of the axis occurs (in fact, developing endurance athletes have the biggest hearts and ventricular cavity sizes among the athlete cohort) [15]. The wall thickness remains within the normal ranges for a healthy individual which is indicative for eccentric hypertrophy [16]. Morphological characteristics of the heart of ski racers influence cardiac electric potential distribution on the body surface. For example, it has been previously demonstrated that the amplitudes of cardioelectric field extrema differ in weight-lifting and ski racers at rest [17].

However, when the body of an athlete is exposed to physical exercise challenge, not only electrical processes emerging in the cardiomyocytes, but also other factors influencing distribution and reflection of electrical processes from the heart muscle onto the body surface may affect the amplitude and time characteristics of the cardiac potentials. It is important to mention the Brody effect, which is a change in the electrical myocardium heterogeneity with an increase in the intracavitary blood volume which occurs in the heart in response to the rise in venous return during FE. The altered position of the heart within the thorax, expansion of the diaphragm and filling the lungs with air, and blood filling of the pericardial vessels cause changes in the resistance of the heart surrounding tissues and formation of the cardiac electric potentials on the body surface [18–21].

Varying electrical conductivity of the organs and tissues in the thorax during redistribution of biological fluids affects reflection of the heart electrical activity onto the torso surface [22, 23]. It is known that the volume of circulating blood in athletes with predominant endurance development increases during transition from the PS to the CS and biochemical composition of the blood changes significantly [5]. The effects of intra- and extracardiac factors of transmission of a signal to the cardiac potentials recorded from the torso surface should be taken into account, because training and competition micro- and mesocycles in athletes may last for months and continuous training during the period from the preparatory cycle to the CS entails changes in the electrical, biochemical, and hemodynamic processes in all elements of the cardiovascular system.

CONCLUSIONS

Thus, cardioelectrotopographic study of the electrical activity of the heart of ski racers has identified alteration in the underlying structure of the ventricular repolarization process at different stages of the training cycle with an insignificantly changed T_{II} wave recorded in the ECG in standard leads. At the competition stage compared to the preparatory stage after performing FE, the duration of early ventricular repolarization (the Tpeak–Tend_{II} interval), significantly decreased, the amplitude of negative extremum significantly increased, and the dynamics of the cardioelectric field extrema changed. The high informative value of the cardioelectrotopographic study in ski racers has shown promise for its introduction into the sports physiology for the assessment of the functional state of the body.

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Translated by I. Matiulko