

PERSONALIZED ANALYSIS OF CARDIAC REMODELING AT THE END OF THE PREPARATORY PERIOD IN CROSS-COUNTRY SKIERS STRATIFIED BY MOVEMENT SPEED

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Abstract. Aim. This study provides an individualized analysis of cardiac remodeling in qualified cross-country skiers stratified by movement speed and identifies characteristics reflecting individual mechanisms of adaptive structural and functional changes in the cardiac hemodynamic system at the end of the preparatory period. **Materials and methods.** The study involved male athletes who provided written informed consent, underwent a medical examination, and were approved for training and competitive loads. Based on physical performance testing during double poling on a Concept 2 SkiErg (USA), cross-country skiers (n = 20) were divided into leader (n = 10) and reserve groups (n = 10) according to movement speed (km/h). From each group, athletes with the highest and lowest physical performance values relative to the group mean were selected: Leader 1 and Leader 10, Reserve 1 and Reserve 10, respectively. Cardiac morphometric measurements were obtained via transthoracic echocardiography (ECG) using a Mindray DC-70 (China) system in compliance with international ECG protocols. **Results.** Cross-country skiers demonstrated adaptive cardiac changes characteristic of high-intensity exercise. The leader group mainly showed changes associated with increased diastolic function and cardiac volumes. In the reserve group, adaptation manifested as myocardial hypertrophy and contractile changes, which may be less efficient. **Conclusion.** The results obtained contribute to a deeper understanding of individual adaptive changes in athletes and help optimize the training process.

Keywords: cardiac remodeling, cross-country skiers, echocardiography, adaptation to exercise, myocardial hypertrophy

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ПЕРСНИФИЦИРОВАННЫЙ АНАЛИЗ РЕМОДЕЛИРОВАНИЯ СЕРДЦА В КОНЦЕ ПОДГОТОВИТЕЛЬНОГО ПЕРИОДА У ЛЫЖНИКОВ-ГОНЩИКОВ, ДИФФЕРЕНЦИРОВАННЫХ ПО СКОРОСТИ ДВИГАТЕЛЬНЫХ ДЕЙСТВИЙ

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Аннотация. Цель: провести персонифицированный анализ ремоделирования сердца у квалифицированных лыжников-гонщиков, дифференцированных по скорости двигательных действий, выявить особенности, отражающие индивидуальные механизмы адаптивных структурно-функциональных перестроек кардио-гемодинамической системы в конце подготовительного периода. **Материалы и методы.** В исследовании на основе письменного информированного согласия приняли участие спортсмены мужского пола, прошедшие медицинское обследование, имеющие допуск к тренировочным и соревновательным нагрузкам. Предварительно, по результатам тестирования физической работоспособности на лыжном эргометре Concept 2 Ski-Erg (USA) одновременным бешажным ходом, лыжники-гонщики (n = 20) были дифференцированы на группы «лидеров» (n = 10) и «резерв» (n = 10) по показателям скорости двигательных действий (км/ч). Из каждой группы были выделены спортсмены с самыми высокими и самыми низкими показателями физической работоспособности по критерию скорости двигательных действий относительно средних групповых значений: лидер № 1 и лидер № 10, соответственно резерв № 1 и резерв № 10. Морфометрические показатели сердца определяли по трансторакальной эхокардиографии на аппарате Mindray DC-70 (Китай) в соответствии с международными эхокардиографическими протоколами. **Результаты.** У лыжников-гонщиков наблюдаются адаптивные изменения сердца, характерные для высоких физических нагрузок. У спортсменов-лидеров преобладают изменения, связанные с увеличением диастолической функции и объемов сердца. У спортсменов из группы резерва адаптация проявляется в виде гипертрофии миокарда и изменений сократительной функции, что может быть менее эффективным. **Заключение.** Полученные результаты позволяют более полно понять индивидуальные адаптационные изменения организма спортсменов и оптимизировать тренировочный процесс.

Ключевые слова: ремоделирование сердца, лыжники-гонщики, эхокардиография, адаптация к нагрузкам, гипертрофия миокарда

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Introduction. It is well known that when training loads are adequate, athletes develop neurovegetative regulation of the circulatory system that ensures economization of cardiac function. This process is characterized by marked bradycardia and a predominance of parasympathetic heart rate regulation at rest, which reduces myocardial oxygen consumption and increases the diastolic phase of the cardiac cycle [2]. Prolonged endurance training, as the principal mechanism of cardiac adaptation, typically leads to an increase in left ventricular (LV) end-diastolic dimension and a corresponding balanced increase

in LV myocardial mass (eccentric hypertrophy), with normal LV wall thickness [14].

Differences in the formation of an “athlete’s heart” among sports primarily concern the extent and combination of myocardial hypertrophy and cavity dilation [9, 12]. According to previous findings, “athlete’s heart” develops either through an increase in the thickness of the LV posterior wall under predominantly endurance loads or by lengthening myocardial fibers when loads are variable and frequently involve short bursts of maximum intensity [2, 19]. The most significant changes are noted in the earliest years of sports

training, eventually stabilizing with systematic prolonged training [8].

Within the concept of “athlete’s heart” remodeling [4], the authors highlight various patterns of functional changes: a gradual expansion of functional capabilities; a stable functional state; an increase in functional potential; and instability of functional parameters. In athletes, an adequate functional state of the cardio-hemodynamic system in response to exercise is achieved by a complex interplay of different cardiac adaptation mechanisms, the features of which depend on the nature of the physical activity [10]. An increase in cardiac output via blood return to the heart (isotonic hyperfunction) is realized by elevated stroke volume and minute blood flow, accompanied by mild myocardial hypertrophy and dilation of its chambers, thereby enhancing cardiac efficiency. In contrast, isometric hyperfunction occurs when resistance to blood ejection (into the aorta and pulmonary artery) is elevated, leading to increased systolic tension and intraventricular pressure. This is energetically more demanding and less efficient, as it results in marked myocardial hypertrophy and chamber dilation [7].

It should be noted that no standardized echocardiographic parameters have been established for qualified athletes in different sports. Existing publications demonstrate wide variability in echocardiographic indices. Individual differences in the mechanisms underlying athletic performance, including the degree of adaptive functional and metabolic changes, are significant and can determine the limiting factors for achieving peak athletic performance [15].

Materials and methods. Based on written informed consent, male cross-country skiers who

had undergone medical examination and were cleared for training and competitions participated in the study. Preliminary testing of physical performance was carried out using a Concept 2 Ski-Erg (USA) device with the double-poling technique. According to movement speed (km/h), the athletes ($n = 20$) were categorized into “leaders” ($n = 10$) and “reserve” ($n = 10$). From each group, athletes with the highest and lowest physical performance indicators (relative to group averages) were identified: Leader 1 and Leader 10, Reserve 1 and Reserve 10.

Morphometric parameters of the heart were assessed via transthoracic echocardiography on a Mindray DC-70 (China) device, following international echocardiographic protocols [3, 21]. Linear and volumetric parameters of the cardiac chambers were measured according to international standards [11]. The following indices were evaluated: left atrial (LA) size (cm) and volume (ml), LV end-diastolic dimension (EDD, cm) and volume (EDV, ml), LV end-systolic dimension (ESD, cm) and volume (ESV, ml), posterior wall thickness (LVPW, cm) and interventricular septum thickness (IVS, cm), LV stroke volume (SV, ml), aortic and pulmonary artery diameters (cm), LV myocardial mass (LVMM, g) and LV myocardial mass index (LVMMI, g/m²), ejection fraction (EF, %). Additionally, the EDV/LVMM ratio was calculated to determine the relationship between dilation and hypertrophy.

Results. The results summarizing the individual characteristics of the cross-country skiers at the end of the preparatory period are presented in Table 1.

All participants were males aged 19–25 years, an age of maximal cardiovascular adaptation to

Table 1
Таблица 1

Morphometric and Qualification Indicators of Cross-Country Skiers
Морфометрические и квалификационные показатели лыжников-гонщиков
в конце подготовительного периода

Parameter	Leader 1 ($n = 1$)	Leader 10 ($n = 1$)	Reserve 1 ($n = 1$)	Reserve 10 ($n = 1$)
Age, years	22	21	19	20
Body mass, kg	74.10	72.20	76.80	64.20
Height, cm	181.00	178.00	178.00	176.00
Body Mass Index, a. u.	22.62	22.78	24.24	20.72
Training experience, years	7	10	9	10
Qualification	MS	MS	1st class	CMS
Speed, km/h	19.70	18.64	18.57	16.21

Note: MS – Master of Sport; CMS – Candidate Master of Sport.

Table 2
Таблица 2

Individual Echocardiographic Indicators of Cross-Country Skiers
Индивидуальные показатели параметров эхокардиограммы лыжников-гонщиков
в конце подготовительного периода

Parameter	Leader 1	Leader 10	Reserve 1	Reserve 10	Normative Range*
LA size, cm	3.80	3.20	3.40	3.83	3.00–4.00
LA volume, ml	44.00	34.00	47.44	–	18.00–58.00
LV EDD (cm)	5.60	5.90	5.37	5.90	4.20–5.90
LV ESD (cm)	3.50	3.20	2.80	4.05	2.50–3.98
Δ (EDD–ESD), cm	2.10	2.70	2.57	1.85	> 1.86
EF, %	68.00	74.00	78.80	62.90	52.00–72.00
Aortic diameter, cm	3.20	3.40	3.20	3.10	2.20–4.40
Pulmonary artery, cm	2.3	2.5	2.5	2.4	< 2.80
LVMM, g	290.00	225.00	213.02	271.10	88.00–224.00
LVMMI, g/m ²	145.20	123.00	119.25	147.20	50.00–102.00
SV, ml	105.00	127.00	109.96	105.70	40.00–123.00
LVPW thickness, cm	0.90	1.00	1.03	1.23	0.60–1.00
IVS thickness, cm	0.90	0.90	1.03	1.23	0.60–1.00
IVS / LVPW	1.0	0.9	1.0	1.0	< 1.00
EDV, ml	54.00	174.00	139.51	167.70	67.00–155.00
ESV, ml	49.00	47.00	29.55	62.00	22.00–58.00
EDV / LVMM	0.53	0.77	0.65	0.61	0.70–1.00

*Normative range for a healthy population [18].

high-intensity loads in endurance sports [1]. Body mass varied by up to 16.4% between Reserve 1 (76.80 kg) and Reserve 10 (64.20 kg), while height differed by no more than 2.7%. Body Mass Index (BMI) remained within normal limits (18.5–24.9). Training experience ranged from 7 to 10 years.

Table 2 presents individual echocardiographic parameters of the skiers in absolute values.

The linear and volumetric parameters of the left atrium, as well as the diameters of the aorta and pulmonary artery, aligned with normative reference values [18]. Other parameters revealed personalized patterns of structural and functional remodeling.

Leader 1. Most parameters remained within upper normative limits, except LVMM and LVMMI, exceeding the upper normal range by 29.5% and 29.8%, respectively. Posterior LVPW and interventricular septum IVS thickness values suggest mild myocardial hypertrophy within physiological limits. Low EDV/LVMM and IVS/LVPW ratios near 1.0 indicate that performance is supported by higher LVMM and end-

diastolic volume, characteristic of an endurance-trained heart.

Leader 10. Key remodeling features included high LV EDD at the upper normative limit and EDV exceeding the recommended range by 13.54%. SV slightly exceeded normal values and was 17.3% higher than in Leader 1. The EDV/LVMM and IVS/LVPW ratios were within normal limits. By the end of the preparatory period, this athlete's cardiac function was primarily supported by enhanced diastolic capacity.

Reserve 1. The values for IVS and LVPW thickness (and their ratio) approached the upper limit of normal. EF was 8.6% above the upper recommended boundary, whereas ESV was significantly lower than that of Leader 1 (by 65.8%) and Leader 10 (by 59.1%). Thus, the main adaptation involved enhanced contractile function, which requires higher oxygen consumption and may represent a less efficient adaptive strategy.

Reserve 10. Both EDD and ESD reached the upper normative boundaries, and EDV and ESV exceeded them. LVMM was 17.40% above the reference, while IVS and LVPW thickness

were elevated by 23.0%. The EDV/LVMM ratio was below 0.70, indicating marked myocardial hypertrophy, decreased EF, and an increased end-systolic volume. This athlete requires more frequent medical monitoring.

Discussion. In endurance athletes, moderate eccentric LV hypertrophy commonly reflects adaptive mechanisms. Functional adaptation is primarily associated with an elevated stroke volume during exercise [7], facilitated by greater LV distensibility in diastole and a steeper Frank-Starling relation [13]. In adolescent athletes, average LV end-diastolic dimension is reported at about 5.16 cm (range 4.7–5.8), end-systolic dimension averages 3.25 cm, LV end-diastolic volume 128.17 ml (range 83.6–154 ml), and end-systolic volume 43.08 ml [13]. These results are within normative limits [18].

In qualified male cross-country skiers and biathletes with high training loads, end-diastolic dimension values of 5.1 (4.9–5.5) cm, end-systolic dimension of 3.3 (3.2–3.6) cm, EDV of 124.0 (117.0–147.0) ml, and ESV of 46.0 (40.0–54.0) ml have been reported, alongside LVPW and IVS values of 0.9 (0.8–1.0) cm [6]. The EDV/LVMM ratio is often used to evaluate the effectiveness of cardiac adaptation; it is ideally around 1.0 a.u. [17]. Lower values (< 0.70) suggest dominant plastic changes in the myocardium, consistent with significant hypertrophy [7].

Typically, the LV posterior wall is thicker than the interventricular septum, so $IVS/LVPW < 1.0$ is considered normal. A ratio > 1.0 is recognized as a key sign of LV hypertrophy [16]. Nevertheless, permissible LV wall thickness for highly trained athletes is sometimes cited up to 1.3–1.5 cm [5]. In some endurance-trained male athletes, LVPW of 1.1 ± 0.02 cm and IVS of 1.02 ± 0.02 cm were described, along with $IVS/LVPW = 0.92$, $EDD = 5.69 \pm 0.07$ cm, $EDV = 160.86 \pm 8.73$ ml, $LVMM = 167.45 \pm 9.09$ g, and $EDV/LVMM =$

$= 0.96 \pm 0.03$ [8]. Other research on cross-country skiers reported $IVS = 1.34 \pm 0.01$ cm, $LVPW = 0.89 \pm 0.01$ cm, $LVMMI = 170.51 \pm 32.54$ g/m², and $EF = 44.65 \pm 8.3\%$ [20].

Conclusion. Comparisons between our findings and published data show that linear LV dimensions display relatively moderate variability, whereas volumetric parameters differ more noticeably. In highly qualified athletes, $IVS/LVPW$ typically does not exceed the permissible upper limit.

A personalized Echo-CG analysis of cross-country skiers from both leader and reserve groups at the end of the preparatory period revealed:

- leader 1 requires continuous monitoring due to a high LV myocardial mass (LVMM) that, if further increased, may pose health risks;

- leader 10 predominantly adapts through enhanced diastolic LV function. Although SV and EF are high, this does not guarantee optimal adaptation and could potentially lead to cardiac insufficiency if compensatory mechanisms become exhausted;

- reserve 1 shows stronger reliance on contractile mechanisms, demanding higher oxygen consumption and potentially reflecting a less efficient adaptation process;

- reserve 10 exhibits LV myocardial hypertrophy (LVMM surpassing the norm by 17.4%), with IVS and LVPW thickness 23.0% above the upper limit and a low EDV/LVMM ratio. These factors are associated with reduced EF and higher end-systolic volume, indicating the need for close medical supervision.

Overall, the data highlight substantial individual variability in cardio-hemodynamic remodeling, even within a single sport specialization. These findings underscore the importance of regular medical follow-up and personalized adjustments to optimize training and protect athletes' cardiovascular health.

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