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Dynamics of *TP*, *HF*-, *LF*-, and *VLF*-Waves of the Cardiointervalogram (in Clinostasis Conditions) of an Elite Ski Racer in the Preparatory, Competition, and Transition Periods Depending on the Volume and Intensity of Training Loads

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Abstract—In order to study the mechanisms of adaptation to loads requiring high endurance, a cardiointervalogram (CIG) of a 27-year-old Master of Sports of Russia in cross-country skiing was repeatedly recorded under clinostasis conditions, with estimation of the total power (*TP*) of the spectrum, as well as the absolute power (ms^2) of *LF*-, *HF*-, and *VLF*-waves and the relative power of these waves (as a percentage of *TP*), i.e., *LF%*, *HF%*, and *VLF%*. They were compared with the volume (V_{km}, V_{min}) and intensity (N_{hr}) of training loads. The volume of loads was maximum in the preparatory period (21 km/day) and minimum in the transition period (18 km/day), and their intensity was stable throughout the annual cycle (working pulse, 120–121 bpm). With the change in the volume of loads, the values of the CIG indices also changed. For example, in the preparatory period, the medians of *TP*, the power of *HF*-, *LF*-, and *VLF*-waves, as well as *VLF%* increased; in this period, with an increase in the volume of loads (V_{km}), the values of *VLF%* increased. In the competition period, the medians of *TP*, the power of *HF*-, *LF*-, and *VLF*-waves, and *VLF%* remained at a high level. In the transition period, the medians of *TP*, the power of *HF*-, *LF*-, and *VLF*-waves, as well as *LF%* and *VLF%*, decreased, whereas the median *HF%* increased. For the annual cycle, a direct dependence of the median *TP* on the volume of loads (V_{km}) and the median power of *VLF*-waves on the volume (V_{km}) and intensity (N_{hr}) of the load was revealed. It is assumed that the values of *TP*, as well as *HF*-, *LF*-, and *VLF*-waves, and *VLF%* (in clinostasis) reflect the influence of the parasympathetic part of the autonomic nervous system on the heart (*VLF%* probably reflects the intensity of synthesis of non-neuronal acetylcholine by cardiomyocytes, whereas *LF%* and *HF%* values reflect the formation of anxiety in connection with upcoming starts).

Keywords: cross-country skiing, adaptation to physical exercise, autonomic nervous system, heart rate variability, total spectrum power, absolute and relative power of *HF*-, *LF*-, and *VLF*-waves, periods of the annual cycle of skiers

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INTRODUCTION

The processes of adaptation to physical loads that require endurance are influenced by the volume and intensity of training sessions; however, the nature of this influence from a physiological point of view was studied insufficiently [1, 2].

In view of above, the goal of this study was to assess by means of cardiointervalography (CIG) the nature of changes in the regulation of heart activity in an elite skier over three periods of the ski season (preparatory, competition, and transition) depending on the volume and intensity of the training load.

The method for assessing the state of the autonomic nervous system (ANS) by the heart rate variability (HRV) is widely used in clinical practice, and the interpretation of its main parameters has been described in detail in the literature [3–7].

In recent years, of the more than 30 HRV parameters, much attention has been paid to the spectral parameters of CIG [3–5, 7]. The latter include (1) the total power (*TP*) of the spectrum, reflecting the power of rhythm oscillations in the frequency range from 0.003 to 0.5 Hz, i.e., the total effect of the sympathetic (SP) and parasympathetic (PP) parts of the ANS and a number of biologically active substances (BAS); (2) the power of high-frequency (*HF*) waves, i.e., the power of oscillations with a frequency of 0.15 to 0.40 Hz, reflecting the influence of the PP of the ANS on the heart; (3) the power of slow (low-frequency, *LF*) waves, i.e., the power of oscillations with a frequency of 0.04 to 0.15 Hz, reflecting the effect of the SP of the ANS on the heart, which is modulated by the baroreflex; and (4) the power of very slow (very low-frequency, *VLF*) waves, ie., the power of oscillations with a frequency of 0.003 to 0.04 Hz, which probably reflects the complex effect of SO and PO of the ANS, as well as a number of BAS, on the heart. It is believed that the relative power of *HF*-, *LF*-, and *VLF*-waves, expressed as a percentage of *TP* (i.e., *HF%*, *LF%*, and *VLF%*), reflects the specific contribution of the corresponding parts of the ANS and BAS to the regulation of the activity of the heart.

CIG has been widely used in sports practice to assess the state of an athlete at training camps and competitions [8–11]. However, little attention has been paid to the dependence of HRV parameters in endurance athletes on the periods of annual training cycle (preparatory, competition, and transition) and the volume of training loads. In view of this, the goal of this study was formulated. Due to the fact that the transition period is usually implemented at home, CIG was performed in all three periods of the annual cycle on one elite skier K.D. (the first author of this article), taking into account the volume of his training loads in all three periods.

Before describing the methods and main results of this study, a number of important points should be noted.

It was noted [3, 9, 12, 13] that data on the dynamics of the absolute power of *HF*-, *LF*-, and *VLF*-waves, as well as the dynamics of the relative power of these waves expressed as a percentage of *TP* (i.e., *HF%*, *LF%*, and *VLF%*), for skiers during the annual cycle are scarce and ambiguous. For the *TP* value, it is shown that it varies from 1515 to 14486 ms^2 and increases with the improvement of sportsmanship. Very little is known about the dependence of *TP* values on the period of the sports season and on the volume and power of the training load of athletes, although indirect data from a number of authors indicate that, in the preparatory period (i.e., at high training volumes), the activity of the PP of the ANS in elite skiers continues to increase [9, 14, 15]. This is consistent with the idea that endurance training increases the activity of the PP of the ANS [3, 9, 14, 15]. However, the issue of the specific mechanisms of vagotonia formation during endurance training requires a detailed study. From this standpoint, it is of great interest to analyze HRV parameters in elite athletes throughout all three periods of their next annual cycle (season) taking into account the volume and power of training, which was the main goal of this study.

It is important to note that the volume and intensity of training loads are expressed in different ways. Foreign authors [11, 16–19] estimate the load volume by the duration of training (min/day; h/day), whereas Russian authors [20, 21] estimate it by the length of the training path (km/day). The intensity or power of load is estimated by the "working pulse" value [11, 17, 21, 22]. It is generally accepted [23, 24] that the working pulse values can reflect five intensity zones, the first three of which (50–80% of HR_{max}) are regarded as low-intensity zones, and zones 4 and 5 (i.e., higher than 80% of HR_{max}) are regarded as high-intensity zones. The annual volume of training loads of elite skiers is huge: it varies from 700 to 937 h [17, 18] or from 9150 to 9493 km [21, 22]. The training load volume for each elite cross-country skier is individual, because it depends on the level of training, rate and quality of recovery processes, and other factors [24, 25]. The goal of the coach and athlete is to come to the crucial (prestigious) start with the maximum level of readiness [24].

MATERIALS AND METHODS

The study involved a 27-year-old cross-country skier (K.D.), master of sports of Russia, member of the Tatarstan cross-country skiing team, multiple champion and prize-winner of all-Russian and international ski racing competitions among juniors and youths. K.D. has 17 years of experience in cross-country skiing. The studies were performed from March 2019 to June 2020.

The physical performance of K.D. was tested in a sports dispensary in Kazan on a Concept2 SkiErg ski simulator (United States), which simulates the movements of a simultaneous stepless skiing. It was found (Table 1) that, when exhaustive muscular work in a stepwise increasing manner until "failure" was performed at the beginning of the preparatory period (June 2019), the maximum oxygen consumption (MOC) was 64.5 mL/kg or 4418 mL; the aerobic threshold (AeT), i.e., the heart rate (HR) at which there is still no rise in lactate during muscle exercise, was 113 bpm; the anaerobic threshold (AnT), i.e., the HR at which lactate concentration began to rise was 171 bpm; the maximum heart rate (HR_{max}), which is achieved when performing work of maximum power (when load increases every 2 min by 20 W), was 185 bpm; the maximum operating power (N_{max}) reached 290 W, and the maximum rise in the lactate concentration (L_{max}) was 8.52 mM. A similar test performed at the end of the summer–autumn training, i.e., before "enrolling" (October 2019) showed (Table 1) that the MOC was 69.3 mL/kg or 4845 mL, AeP was

Table 1. Assessment of the level of physical performance and functional state of the key energy supply systems of athlete K.D. during implementation of exhaustive muscular work of a stepwise increasing nature to "failure" (on the Concept2 Ski-Erg ski simulator and treadmill, according to the data of the sports dispensary (Kazan))

Parameter analyzed	June 2019		October 2019	
	Concept2SkiErg	Treadmill	*Concept2SkiErg*	Treadmill
MOC, mL/kg/min	64.5	65.8	69.3	74
AeP, bpm	113	154	111	142
AnP, bpm	171	170	164	170
HR_{max}, bpm	185	188	185	192
N, W or V, km/h	290 W	12 km/h	310 W	13.5 km/h
L_{max}, mM	8.52	9	10.7	9.48

111 bpm, Anp was 164 bpm, HR_{max} was 185 bpm, N_{max} was 310 W, and L_{max} was 10.7 mM. Tests on a treadmill with a track slope of 10° at stepwise increasing loads (every 2 min) until "failure" showed (Table 1) that, at the beginning of the preparatory period (June 2019), the MOC was 65.8 mL/kg or 4740 mL, AeP was 154 bpm, Anp was 170 bpm, HR_{max} was 188 bpm, the maximum running speed for 2 min was 12 km/h, and L_{max} was 9 mM. At the end of the summer–autumn preparatory period (October 2019), the MOC was 74 mL/kg or 5173 mL, AeP was 142 bpm, Anp was 170 bpm, HR_{max} was 192 bpm, the maximum running speed for 2 min was 13.5 km/h, and L_{max} was 9.48 mM. Thus, tests of the physical performance of athlete K.D. on the Concept2 SkiErg ski simulator and on the treadmill showed similar results, which give grounds to postulate that (1) athlete K.D., indeed, belongs to the group of elite ski racers and (2) during the preparatory period, his performance increases.

According to the literature, the absolute MOC values in six Swedish elite cross-country skiers were 5.1 ± 0.1 L/min [26–28].

Importantly, the training camps (TCs) and competitions were held in different regions of Russia and abroad, including the plains and mountains (Table 2). During these trainings, the first author of this article (i.e., athlete K.D.) recorded the volume and power of his training loads and performed self-recording of CIG.

The volume of training loads (V_{km}, V_{min}) of athlete K.D. for each day that preceded the morning CIG recording, was evaluated by summing up the time spent on all workouts and morning exercises, which was expressed in min/day (V_{min}), as well as in kilometers of cross-country skiing, roller skiing, or cross-country running (V_{km}). The intensity or power (N_{HR}) of the training loads was assessed by the mean HR_{work} recorded during each training session with a POLAR 430 heart rate monitor equipped with a GPS sensor (POLAR, Finland). According to the POLAR programs, the HR_{work} value made it possible to attribute the load intensity to one of the five training zones specified above [23, 24].

It should be noted that 5-min CIG self-recording was performed in the subjects in the supine position after night sleep (before breakfast) in comfortable conditions using a VNS-Micro system (Neurosoft, Russia), and CIG analysis was performed using the Poly-spectrum software (Neurosoft, Russia). Along with other parameters, we evaluated the following HRV parameters: the total power of the spectrum (*TP*, ms^2); the absolute power of *HF*-, *LF*-, and *VLF*-waves (ms^2), as well as the relative power of these waves expressed as a percentage of *TP* (i.e., *HF%*, *LF%*, and *VLF%*). The assessment of these parameters was formed by summing up the results of individual studies conducted in each month of the corresponding period, which made it possible to evaluate statistically significant differences between the values of the parameters recorded in one month (period) from those recorded in another month (period). In total, athlete K.D. performed 217 CIG self-recordings, of which 84 were performed during the preparatory period, 74 during the competition period, and 59 during the transition period. All these HRV parameters, as well as V_{min}, V_{km}, and N_{HR} were calculated for each month of the annual cycle and in general for each of the three periods (preparatory, competition, and transition) of the annual cycle. They were expressed as

Table 2. Schedule and places of training camps (TCs) and competitions of athlete K.D. in 2018–2019 and 2019–2020 seasons

Season 2018–2019

competition period (March–April 2019)	transition period (May 2019)
1. TC in Khmelevskie Lakes n/p (Krasnodar Territory)*	1. Workouts at home (Kirov oblast)
2. ChR (Arkhangelsk oblast)	
3. ChR (Murmansk oblast)	

Season 2019–2020

preparatory period (June–November 2019)	competition period (December 2019–March 2020)	transition period (April–June 2020)
1. TC in Raubichi Village (Belarus)	1. Stage 1 of CR (Khakassia)*	1. Workouts at home (Kirov region)
2. TC in Izhevsk (Udmurtia)	2. Stage 2 of CR (Perm Territory)	
3. TC in Belmeken s/b (Bulgaria)*	3. TC in Perekop Village (Kirov oblast)	
4. TC and SChR in Tyumen	4. Stage 3 of CR (Tatarstan)	
5. ChL of the Republic of Tatarstan in Zainsk (Tatarstan)	5. TC in Novosibirsk	
6. Workouts at home (Kirov)	6. VFDCh in Perekop Village (Kirov oblast)	
7. TC in St. Petersburg	7. Eastern Europe CC in Syktyvkar (Komi Republic)	
8. TC in Ergaki n/p (Krasnoyarsk Territory)	8. TC in Novosibirsk	
9. TC in Vershina Tei Village (Khakassia)	9. CRF (Arkhangelsk oblast)	
	10. TC in Khmelevskie Lakes n/p (Krasnodar Territory)*	

Designations: *—mountain climatic conditions (heights over 900–2000 m above sea level; TC—training camp; CR—championship of Russia; SChR—summer championship of Russia; SChRT—summer championship of the Republic of Tatarstan; CR—Cup of Russia; VFDCh—Volga Federal District championship; CC—continental cup; CRF—Cup of Russia final; n/p—natural park; s/b—sports base.

Table 3. Median, 25th and 75th percentiles (bottom row) of the volume (V_{km}, V_{min}) and intensity (N_{HR}) of training loads of elite skier K.D. by months, as well as *TP* (ms^2), absolute power of *HF*-, *LF*-, and *VLF*-waves (ms^2), and relative (in % of *TP*) power of these waves (according to cardiointervalography data under clinostasis conditions)

Date	Loads			*TP*	*HF*-waves		*VLF*-waves		*LF*-waves	
	V_{km}, km/day	V_{min}, min/day	N_{HR}, bpm	ms^2	ms^2	%	ms^2	%	ms^2	%
Competition period										
Mar. 2019	21.5 14/25	93 65/109	124 119/131	8080 6767/8979	3540 2830/4124	45.0 35/53	2236 1661/3107	29.4 22/40	1892 1452/2238	25.8 19/27
Apr. 2019	14.8 9/23	61 45/90	112 106/123	9300 6930/10865	3475 3383/393	43.3 38/49	2227 1985/3239	29.3 25/34	2520 1578/2957	25.4 9/31
Transition period										
May 2019	15.5 9/24	101 72/146	124 112/130	6879 5665/10286	3065 1953/4218	35.4 31/47	2846 1731/5186	49.1 35/49	1249 1182/1301	16.2 14/20
Preparative period										
June 2019	22.5 18/38	122 104/158	125 115/130	9764 6958/10789	3065 1953/4218	41.0 33/46	3333 2367/3968	35.4 30/43	2188 1443/3132	21.1 19/24
July 2019	25.2 12/44	124 103/166	122 111/125	9378 6518/11178	3748 3285/4464	42.8 37/48	3198 2180/4588	37.4 32/43	1763 1314/2405	19.8 17/25
Aug. 2019	20.6 13/31	129 90/154	117 112/131	11099 9227/12697	4930 4334/5121	44.9 39/49	3200 2267/3602	31.1 26/35	2912 1528/2974	21.8 19/30
Sept. 2019	21.7 12/28	100 83/133	115 110/124	9646 6601/10155	3106 2677/4171	41.4 26/47	2894 2193/5464	33.8 24/53	2138 1588/2577	23.4 19/26
Oct. 2019	15.7 9/23	91 71/120	122 109/131	6450 4665/8875	3559 2793/4487	53.4 46/59	1711 1064/2884	27.2 24/30	1132 991/2271	19.9 16/24
Nov. 2019	18.7 13/23	84 63/106	125 117/133	9322 7188/11342	3335 2487/4340	42.5 34/47	2777 2014/3842	31.9 23/39	1853 1298/2730	24.3 19/28

Table 3. (Contd.)

Date	Loads			*TP*	*HF*-waves		*VLF*-waves		*LF*-waves	
	V_{km}, km/day	V_{min}, min/day	N_{HR}, bpm	ms^2	ms^2	%	ms^2	%	ms^2	%
Competition period										
Dec. 2019	21.5 14/26	88 64/121	118 114/128	8282 7559/12023	3764 (2629/4061)	34.1 (28/44)	3072 (2103/4545)	37.1 (29/41)	2032 (1521/2914)	25.4 (22/38)
Jan. 2020	18.6 11/23	72 50/101	124 113/136	7942 6956/8561	2939 2054/3512	39.7 27/46	2698 2292/4038	37.2 27/53	1684 1379/1990	19.8 18/26
Feb. 2020	15.8 12/22	79 53/93	123 114/159	8027 (7171/9341.5)	3523 (2952/4400)	41.1 (38/48)	2555 (1986/3097)	32.2 (25/37)	2253 (1633/3022)	25.6 (22/29)
Mar. 2020	20.2 15/22	94 82/107	115 105/123	8823 (7466/10145)	3840 (3558/3884)	40.0 (38/43)	3361 (2223/3854)	33.2 (30/36)	2485 (2125/2563)	25.0 (23/28)
Transition period										
Apr. 2020	13.5 11/30	92 81/117	113 104/123	5754 5273/6118	2478 2225/2708	46.2 40/48	1977 1537/2268	31.1 29/40	1107 748/1431	20.2 14/26
May 2020	18.7 15/60	119 87/151	119 112/125	8378 6113/8838	3705 2514/3887	45.2 44/51	1779 1556/239	30.6 20/35	1319 1009/2612	20.9 19/25
June 2020	20.4 16/42	111 93/142	120 118/125	7559 6568/8617	3702 3130/3970	49.3 42/53	1769 1271/2222	24.1 20/27	1930 1466/2181	25.0 (21/28)
In general, for the preparatory (1), competition (2), and transition (3) periods										
Prep. 1	21 13/31	106 80/145	121 112/130	9473 6685/11037	3793 2860/4579	44.7 35/52	2818 2075/3874	32.6 24/39	1962 1307/2814	22.5 18/26
Comp. 2	19 12/25	82 61/106	121 111/130	8047 6940/9616	3519 2805/4071	41.7 34/48	2622 2023/3800	32.8 26/40	2032 1570/2619	24.5 20/29
Trans. 3	18 12/37	105 85/142	120 112/126	6961 5349/8416	3371 2387/3896	47.3 41/52	1874 1374/2582	27.7 22/36	1480 1072/2097	21.7 19/27
Statistically significant differences between periods according to Mann–Whitney test										
$p < 0.05$	1–2	–	–	1–3; 2–3	1–3	2–3	1–3; 2–3	1–3; 2–3	1–3; 2–3	1–2

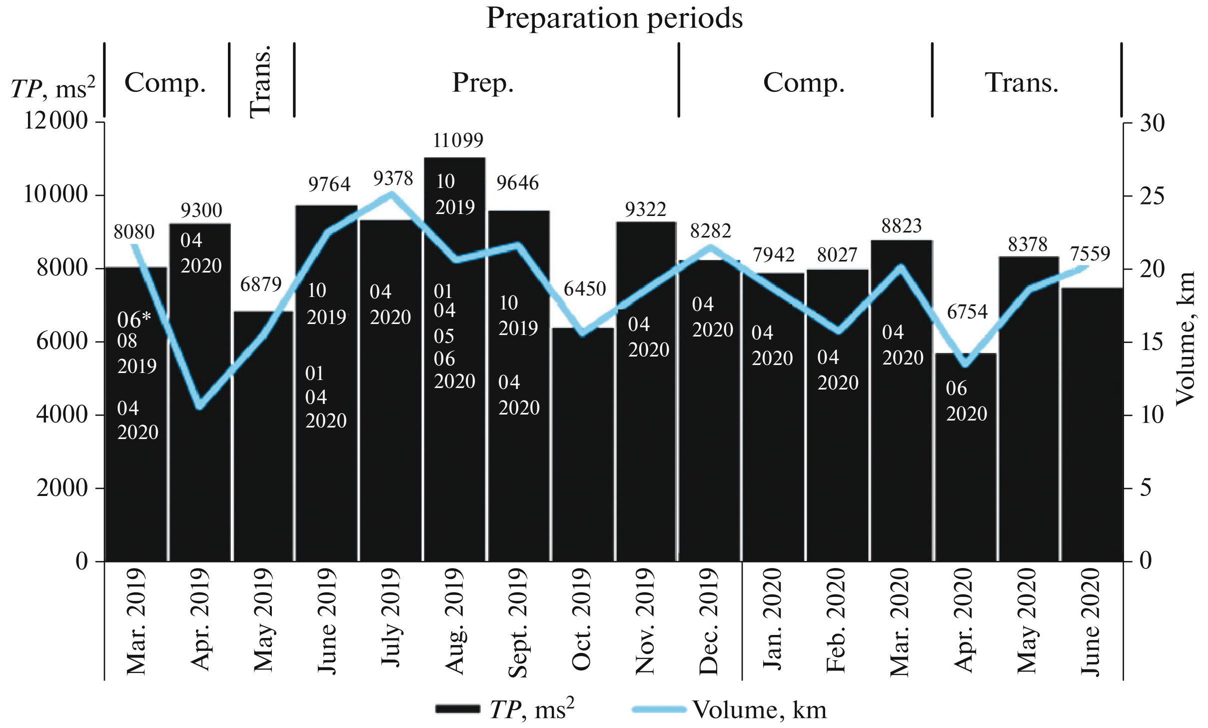

Fig. 1. Dynamics of the values of the total power of the wave spectrum (*TP*, ms^2, columns) and the values of the volume (V_{km}) of the training load (linear plot) of the elite skier K.D. The numbers in the columns reflect the months (top) from which this month (bottom) differs statistically significantly in *TP* values (according to Mann–Whitney test, $p < 0.05$), according to the results of cardiointervalography performed under clinostasis conditions.

the median and 25 and 75 percentiles [29]. Differences were assessed using the Mann–Whitney test and considered statistically significant at $p < 0.05$ [29]. Calculations, including the calculations of Spearman correlation coefficient [29], were performed using the BioStat2009 Professional ver. 5.9.8 software (AnalystSoft, United States).

RESULTS

The main results of the study are summarized in Table 3 and in Figs. 1, 2.

It was established (Table 3, Fig. 1) that the volume of training loads of athlete K.D., expressed in km of the path (V_{km}), in the preparatory period was significantly higher ($p < 0.05$) than that in the competition period (median, 21 vs 19 km/day) and higher than in the transition period (18 km/day, $p > 0.05$). However, the load volume, expressed as V_{min}, was approximately the same in all periods (judging by the fact that the differences between the periods of the annual cycle were statistically nonsignificant), although it had a wave-like dynamics (in the preparatory, competition, and transition periods, the median was 106, 82, and 105 min/day, respectively). In general, the annual (from June 2019 to May 2020) load volume of athlete K.D. amounted to 622 h. Thus, the training load volume of athlete K.D. in all study periods was relatively low as compared to the load volume of famous elite cross-country skiers [11, 17, 18, 20, 21], which is associated with the coach's recommendations to reduce the load due to the coronavirus pandemic (from March to June 2020).

The training load intensity, judging by the values of the working heart rate (N_{HR}) in all periods of the annual cycle, was relatively constant: the median HR_{work} in the preparatory, competition, and transition periods was 121, 121, and 120 bpm, respectively. Taking into account the division to five zones of load intensity [22, 23], 41.4% of training sessions were attributed to zone 1 (97–116 bpm); 37.0% to zone 2 (117–135 bpm), 15.1% to zone 3 (136–154 bpm), 4.8% to zone 4 (155–174 bpm), and 1.7% to zone 5 (175 bpm).

When analyzing the values of *TP*, as well as the absolute and relative power of the *HF*-, *LF*-, and *VLF*-waves of athlete K.D., recorded under clinostasis conditions, the following general patterns were established: (1) the values of these parameters depend on the period of the annual cycle, with each parameter being characterized by its own dynamics; (2) within each period, the values of the parameter periodically (from month to month) change (sometimes increase and sometimes decrease); i.e., their dynamics is oscillatory (Table 3, Fig. 1).

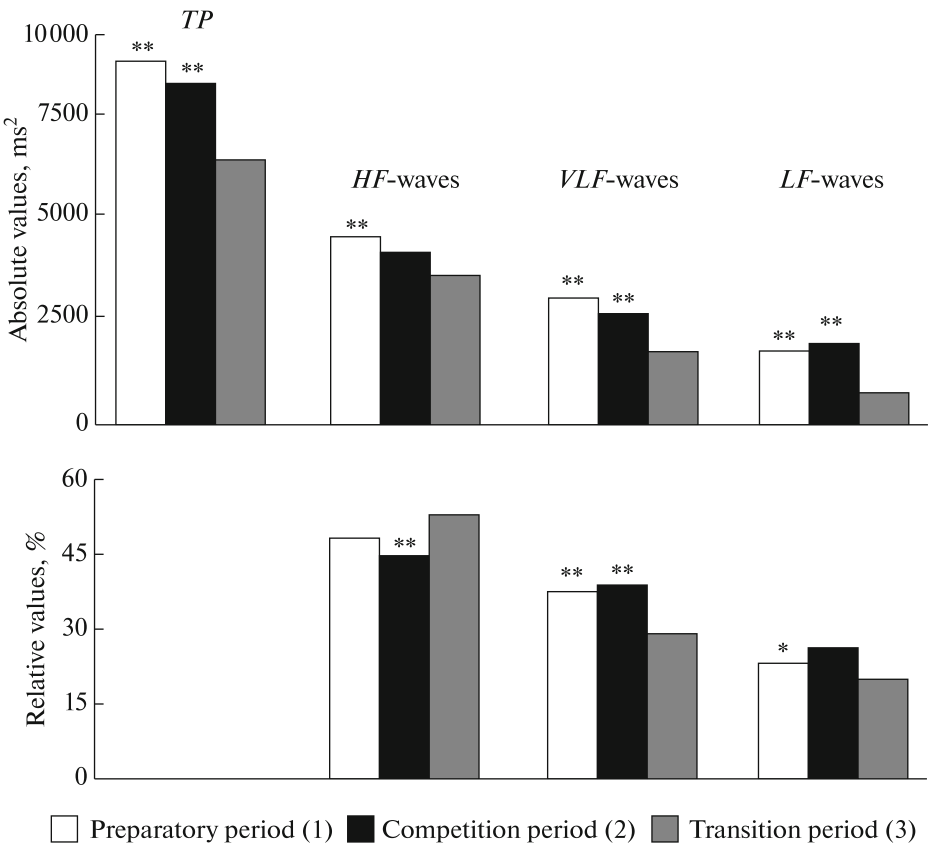

Fig. 2. Dynamics of the values of the median total power *TP* (ms^2), the absolute power of *HF*-, *VLF*-, and *LF*-waves, and the relative power of these waves expressed as a percentage of *TP* (i.e., *HF%*, *VLF%*, and *LF%*) of elite skier K.D. in the preparatory (1), competition (2), and transition (3) periods (the 1st, 2nd, and 3rd columns, respectively), according to the results of cardiointervalography performed under clinostasis conditions. Asterisks above the columns mean that the differences with the competition (*) and/or transition (**) periods are statistically significant according to Mann–Whitney test.

The analysis of the dynamics of the median *TP* in athlete K.D. (Table 3, Fig. 2) showed that, in the preparatory (9473 ms^2) and competition (8047 ms^2) periods, it was higher than in the transition period (6961 ms^2; $p < 0.05$), whereas the differences between the preparatory and competition periods were statistically nonsignificant. Within the preparatory and transition periods, the *TP* values changed from month to month, but in the competition period they were relatively stable (Fig. 1). In each of the three periods, there was no statistically significant dependence of *TP* values on the volume and intensity of training loads. However, over the entire annual cycle in general, a significant ($p < 0.05$) dependence of *TP* on the training load volume (V_{km}) and load intensity (N_{HR}) was found (the Spearman coefficient was +0.18 and +0.17, respectively). This suggests that, as the volume of training loads (V_{km}) and their intensity (N_{HR}) increase, the median *TP* recorded under clinostasis conditions increases. The identified *TP* dynamics, taking into account literature data on the nature of *TP* [3, 7, 16] and our data on the median absolute and relative power of *HF*-waves in athlete K.D. (similarly to other members of the Tatarstan national ski team), indicates that the activity of the PP of the ANS in elite skiers during the sports season is very high. However, it undergoes certain changes: increases in the preparatory period, remains at this level in the competition period, and decreases in the transition period.

It was established (Table 3, Fig. 2) that *the median absolute power of HF-waves (AMHF), reflecting the effect of the PP of the ANS on the heart*, was 3793 ms^2 in the preparatory period, 3519 ms^2 in the competition period, and 3371 ms^2 in the transition period. The differences between the preparatory and transition periods were statistically significant ($p < 0.05$). This is consistent with the literature data, according to which, with an increase in the skill of a cross-country skier, the value of this parameter increases, which is much higher than that of athletes in team sports and martial arts [30]. We found no dependence of *AMHF* on the volume (V_{km}, V_{min}) and power (N_{HR}) of the load, including over the entire annual cycle in general (Spearman's coefficient was +0.12, +0.12, and +0.10, respectively). Thus, *AMHF* (i.e., the absolute power of *HF*-waves) increases in the preparatory period, remains elevated in the competition period, but decreases in the transition period, when the volume and intensity of training loads decrease. Taking into account the nature of *HF*-waves [3–5, 7] it can be postulated that the dynamics of the median *AMHF* recorded in clinostasis indirectly indicates an increase in the effect of the PP of the ANS on the activity of the heart under the influence of endurance training and a decrease in this effect with a decrease in the volume of training loads.

It was shown (Table 3, Fig. 2) that the median relative power of *HF*-waves (i.e., *HF%*) was 44.7% in the preparatory period, 41.7% in the competition period (differences between them were statistically significant, $p < 0.05$), and in the transition period it increased statistically significantly to 47.3% ($p < 0.05$). This means that, in the preparatory and especially in the competition periods, the median *HF%* decreases, whereas in the transition period it increases, which may be due to a decrease in the influence of the SP of the ANS on the work of the heart in the transition period. We found no statistically significant dependence of the median *HF%* on the volume (V_{km} or V_{min}) and intensity (N_{HR}) of training loads, including for the annual cycle (Spearman's correlation coefficient was –0.12, –0.03, and –0.09, respectively).

It was found (Table 3, Fig. 2) that the median absolute power of *LF*-waves (*AMLF*), which, in opinion of the authors of [3–5, 7], reflects the effect of the SP of the ANS on the heart, was 1962 ms^2 in the preparatory period, 2032 ms^2 in the competition period, and 1480 ms^2 in the transition period. The differences between *AMLF* values in the preparatory and competition periods were nonsignificant ($p > 0.05$), whereas the differences between this parameter in these two periods and in the transition period were statistically significant ($p < 0.05$). Thus, the absolute power of *LF*-waves increased in the preparatory period, remained at this level in the competition period, and decreased in the transition period. We found no dependence of *AMLF* on the volume (V_{km}, V_{min}) and intensity (N_{HR}) of the load, including for the entire annual season in general (Spearman's coefficient was +0.11, +0.08, and +0.09, respectively). Taking into account the genesis of *LF*-waves [3–5, 7], it can be postulated that the dynamics of the median *AMLF* indirectly indicates that endurance training increases the effect of the SP of the ANS on the activity of the heart during CIG registration in clinostasis. This is due to the formation of anxiety in the preparatory and, especially, competition periods before the starts, and a decrease in this feeling in the transition period.

It was established (Table 3, Fig. 2) that the median relative power of *LF*-waves (*LF%*) was 22.5% in the preparatory period, 24.5% in the competition period (the differences between them were statistically significant, $p < 0.05$), and 21.7% in the transition period (differences between the preparatory and transition periods were nonsignificant). This means that the median *LF%* in the preparatory period remains at the same level as in the transition period, in the competition period it increases, and in the transition period it decreases again, although statistically nonsignificantly. We found no dependence of the median *LF%* on the volume (V_{km}, V_{min}) and intensity (N_{HR}) of training loads, including the annual cycle in general (Spearman's correlation coefficient was –0.01, +0.02, and +0.01, respectively).

We found (Table 3, Fig. 2) that the median absolute power of *VLF*-waves (i.e., *AMVLF*), which apparently reflects the effect of BAS on the heart [3–5, 7], was 2818 ms^2 in the preparatory period, 2622 ms^2 in the competition period, and 1874 ms^2 in the transition period. The differences between the median *AMVLF* in the preparatory and competition periods were nonsignificant ($p > 0.05$); however, the differences between the values of this parameter in these two periods and in the transition period were statistically significant ($p < 0.05$). Thus, *AMVLF* (i.e., the absolute power of *VLF*-waves) increases in the preparatory period, remains at this level in the competition period, and statistically significantly decreases in the transition period. This dynamics in many aspects is similar to the dynamics of median *TP* and median *AMHF*. We established the dependence of the absolute power of *VLF*-waves on the volume (V_{km}) and intensity (N_{HR}) of the load throughout the entire annual cycle in general, whereas the dependence on the load volume expressed in minutes (V_{min}) was not found (Spearman's coefficient was +0.19, +0.14, and +0.09, respectively).

Analysis of the dynamics of the *median relative power of VLF-waves (i.e., VLF%)* showed (Table 3, Fig. 2) that *VLF%* values in athlete K.D. varied throughout the season from 24.1 to 49.1%. In the preparatory and competition periods, the contribution of *VLF%* to the total spectrum was equally high, i.e., higher than in the transition period (median *VLF%* were 32.6 and 32.8%, respectively, with no differences between them, $p > 0.05$) and lower in the transition period (median, –27.7%; $p < 0.05$). In the preparatory period, a statistically significant dependence of the median *VLF%* on the volume of training loads (V_{km}) was revealed (Spearman's coefficient was +0.24 ($p < 0.05$)). This indicates that, with an increase in the volume of training loads (V_{km}), the median *VLF%* increases. However, for the competition and transition periods, this dependence was statistically nonsignificant (Spearman's coefficient was +0.05 and –0.17, respectively). Probably for this reason, for the annual cycle in general, we found no dependence of *VLF%* on the volume of the load (V_{km} or V_{min}) and on its intensity (N_{HR}) (Spearman's coefficient was +0.12, +0.02, and +0.05, respectively).

DISCUSSION

Regarding the interpretation of the results of the study of the elite skier K.D., five important points should be noted.

(1) It can be assumed that the values of *TP*, the absolute power of *HF*- and *VLF*-waves, and especially the relative power of *VLF*-waves (i.e., *VLF%*) reflect the degree of influence of the PP of the ANS on the heart, because the effect of the PP of the ANS on the heart in elite skiers is significantly higher than in nonathletes or in beginner skiers [3, 9]. This statement is consistent with the generally accepted idea that endurance training significantly increases the activity of the PP of the ANS [2, 14, 15].

(2) Taking into account modern ideas about the ability of the myocardium [31–35] and other tissues [36] to synthesize acetylcholine (ACh), i.e. non-neuronal ACh, it can be assumed that vagotonia, which is characteristic of endurance athletes [2, 14, 15], is due to the fact that, during training, the effect of the PP of the ANS on the heart increases, and the myocardium acquires the ability to synthesize ACh. It is known [31–33] that synthesized ACh is a potent antioxidant that is involved in the elimination of free radicals generated during intense activation of β_1-adrenergic receptors during physical load. This ultimately increases the viability of cardiomyocytes, causes physiological hypertrophy of the myocardium, and increases the performance of the heart as a pump. Evidence for the role of non-neuronal ACh in the origin of sports vagogonia is the published data [3, 37] on the increase in *VLF%* values with an increase in sportsmanship. We have shown that the increase in *VLF%* in athlete K.D. is associated primarily with an increase in the volume of training loads. This means that ACh synthesis in cardiomyocytes is probably activated during high-volume exercise. From this standpoint, the idea of some authors [3–5, 7, 38, 39] that the power of *VLF*-waves reflects the involvement of humoral factors in the regulation of the activity of the cardiovascular system probably most accurately reflects the nature of *VLF*-waves.

What underlies the appearance of the ability of cardiomyocytes to synthesize ACh? Obviously, from the standpoint of the body's adaptation to the loads that require high endurance (i.e., high intensity of adenosine triphosphate resynthesis for a relatively long time), a high level of antioxidants and factors that prevent apoptosis is required. This property is characteristic of ACh [7, 32–34]. It is also known that the synthesis of ACh requires two initial components: choline, which is formed from membrane lipids, and acetyl, which is formed from acetylcoenzyme A, the main source of which is the Krebs cycle [40]. It is known that endurance training increases the intensity of mitochondrial biogenesis, which leads to an expansion of the mitochondrial network both in skeletal muscles and in the myocardium [41–45]. This creates conditions for the constant synthesis of ACh in cardiomyocytes, which is probably facilitated by the increase in the expression of the gene for choline acetyltransferase, which is involved in the synthesis of ACh, in cardiomyocytes [31, 33, 34, 40]. Thus, we can put forward a hypothesis that the increase in *TP* values and, especially, in the relative power of *VLF*-waves (i.e., *VLF%*), which is characteristic of elite skiers, reflects the formation of non-neuronal ACh synthesis in cardiomyocytes. However, this hypothesis requires more solid evidence.

(3) Our data show that, when CIG is recorded under clinostasis conditions, the greatest contribution to the total power spectrum (i.e., *TP*) is made by *HF*-waves (41.7–47.3% of *TP*). *VLF*-waves rank second (27.7–32.6%), and *LF*-waves rank third (21.7–24.5%). Apparently, in conditions of physical activity, this *TP* structure will be different, and *LF*-waves, which reflect the activity of the SP of the ANS modified by the baroreflex, will rank first.

(4) When recording CIG under clinostasis conditions (i.e., in conditions close to basal metabolism), the activity of the sympathetic system is naturally much lower than during physical load. Therefore, the change in the absolute and relative power of *LF*-waves, detected in the course of the skier's annual cycle during clinostatic CIG recording most likely reflects the emotional state of the athlete, including the formation of emotions such as anxiety. In general, this state reaches its maximum in the competition period, which indirectly affects the dynamics of the absolute and relative power of *HF*-waves, but does not affect the dynamics of the absolute and relative power of *VLF*-waves, which reflects primarily the level of production of the non-neuronal ACh by cardiomyocytes.

(5) This point has an applied value. It can be assumed that, if an increase in *TP* and *AMHF* values without an increase in *VLF%* is observed on a CIG of a skier recorded during training under clinostasis conditions, this means that the effect of the PP of the ANS on the heart, indeed, increases, but the synthesis of non-neuronal ACh is not yet activated. If *VLF%* values increase simultaneously with an increase in *TP* and *AMHF* values, this means that the non-neuronal ACh in the myocardium of the athlete is synthesized. Of course, this assumption requires rigorous proofs, which, most likely, can only be obtained in experiments on animals.

CONCLUSIONS

(1) Multiple CIG recordings under clinostasis conditions in an elite skier K.D. throughout the annual cycle, which allows to evaluate HRV such parameters such as *TP*, absolute (ms^2) and relative (as a percentage of *TP*) power of *LF*-, *HF*-, and *VLF*-waves, as well as fixing the volume of training loads (by the path length (V_{km}) or by their duration (V_{min})) and the intensity of

loads (by HR_{work}) showed that the volume of training loads is maximum in the preparatory period (21 km/day or 106 min/day), decreases in the competition period (19 km/day or 82 min/day), and remains at this level (18 km/day) or even increases (105 min/day) in the transition period. The intensity of the training loads in all periods of the annual cycle is uniform: in the preparatory and competition periods, the HR_{work} is 121 bpm, and in the transition period it is 120 bpm.

(2) In the preparatory period, simultaneously with the increase in the volume of training loads, the medians of *TP*, the absolute power of *HF*-, *LF*-, and *VLF*-waves, as well as the relative power of *VLF*-waves (i.e., VLF%) increase. The relative power of *LF*-waves (*LF%*) remains low, and the relative power of *HF*-waves (*HF%*) decreases. It was found for this period that *VLF%* values increase with an increase in the volume of training loads (V_{km}).

(3) In the competition period, against the background of a consistently high volume of training loads, the medians of *TP*, the absolute power of *HF*-, *LF*-, and *VLF*-waves and the median *VLF%* remain at a high level, whereas the median *HF%* remains at a low level and the median *LF%* increases.

(4) In the transition period, with a decrease in the volume of loads, the medians of *TP*, the absolute power of *HF*-, *LF*-, and *VLF*-waves, as well as the medians of *LF%* and *VLF%* decrease, whereas the median *HF%* increases.

(5) For the annual cycle in general, we found a direct dependence of the median *TP* on the volume of loads, V_{km} (the higher the volume, the higher the median *TP*), as well as a direct dependence of the median absolute power of *VLF*-waves on volume (V_{km}) and intensity (N_{HR}) of the load.

(6) A hypothesis was formulated that the *TP*, *HF*-, *LF*-, and *VLF*-waves, as well as *VLF%* values recorded under clinostasis conditions reflect the effect of the PP of the ANS on the activity of the heart, and *VLF%* probably reflects the intensity of synthesis of non-neuronal acetylcholine by cardiomyocytes, whereas the *LF%* and *HF%* values reflect the formation of anxiety due to the upcoming starts.

COMPLIANCE WITH ETHICAL STANDARDS

Ethics approval. All studies were carried out in accordance with the principles of biomedical ethics formulated in the Declaration of Helsinki of 1964 and its subsequent updates and approved by the local bioethical committee of Vyatka State University (Kirov), protocol no. 1 dated January 17, 2020.

Informed consent. Each participant in the study provided a signed voluntary written informed consent after explanation of the potential risks and benefits, as well as the nature of the upcoming study.

Conflict of interest. The authors declare the absence of obvious and potential conflicts of interest related to the publication of this article.

AUTHOR CONTRIBUTIONS

D.A. Kataev: cardiointervalogram (CIG) recordings in the field, analysis of CIG parameters, writing the article, literature analysis; V.I. Tsirkin: head of scientific work, literature analysis, work on the article; N.S. Zavalin: consultation on the use of methods of mathematical statistics; M.A. Morozova: organization of the purchase of the VNS-Micro autonomic tester, due to which the study and consultation on its use were carried out; S.I. Trukhina and A.N. Trukhin: scientific editing and design of the article and the necessary documentation.

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