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AUTONOMIC REGULATION OF THE CARDIOVASCULAR SYSTEM AFTER AWAKENING AND MOTOR ACTIVITY DURING NIGHT SLEEP UNDER CONDITIONS OF PROLONGED ISOLATION: A DESCRIPTIVE STUDY

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Introduction. Adequate night sleep is crucial for maintaining health and optimal performance. Under chronic stressors, such as prolonged isolation, sleep quality and duration become critical determinants of resilience: sleep disturbances can exacerbate psychological distress and impair cognitive functioning. In such conditions, sleep duration becomes a crucial factor affecting the well-being and productivity of a human operator on the following day. However, its role in shaping the processes of morning activation has been insufficiently studied.

Objective. To identify the characteristics of motor activity during night sleep and autonomic regulation after morning awakening in individuals with different sleep durations under conditions of a prolonged isolation experiment.

Materials and methods. The study was conducted within the framework of the international isolation experiment “SIRIUS-23/24” and involved six healthy volunteers (two men, four women; age range: 25–37 years). Based on sleep duration, participants were divided into two groups: a short-sleep group (< 7 h; $n = 4$; two men, two women; aged 27–37) and a longer-sleep group (> 7 h; $n = 2$; both women; aged 25 and 34). Monthly monitoring of motor activity during sleep was carried out using actigraphy, along with ECG recording and sleep characteristics questionnaires completed immediately after awakening. The following parameters were analyzed: heart rate variability indicators (SDNN, TP, VLF, SI, LF/HF), the Kerdo vegetative index, as well as sleep duration, sleep efficiency, and motor activity during sleep. To assess the significance of differences between the identified groups, the non-parametric Mann–Whitney U test was applied.

Results. Participants in the short-sleep group demonstrated lower sleep efficiency and higher motor activity during nighttime hours. In the same group, a relative reduction in sympathetic influences was observed after awakening, evidenced by lower heart rate values (61.5 bpm, $p = 0.049$), Kerdo vegetative index (−9.4 arbitrary units, $p = 0.015$), and SI (48 arbitrary units, $p = 0.04$). At the same time, parasympathetic activity was enhanced, as shown by higher SDNN (59.3 ms, $p = 0.005$) and TP (1994 ms², $p = 0.006$), indicating impaired morning activation. In the long-sleep group, despite better sleep parameters, lower VLF power values were recorded after awakening compared to the short-sleep group ($p \leq 0.05$).

Conclusions. Under prolonged isolation conditions, some crew members exhibited short sleep duration (< 7 h), which was associated with increased motor activity during nighttime sleep, reduced sleep efficiency, and attenuated sympathetic regulation of heart rate after awakening. These findings highlight the need for an individualized approach to sleep schedule optimization to maintain performance and health in extreme environments.

Keywords: isolation; sleep; sleep quality; sleep duration; heart rate variability; motor activity; SIRIUS-23/24 isolation experiment; circadian rhythm

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ВЕГЕТАТИВНАЯ РЕГУЛЯЦИЯ СЕРДЕЧНО-СОСУДИСТОЙ СИСТЕМЫ ПОСЛЕ ПРОБУЖДЕНИЯ И ДВИГАТЕЛЬНАЯ АКТИВНОСТЬ ВО ВРЕМЯ НОЧНОГО СНА В УСЛОВИЯХ ДЛИТЕЛЬНОЙ ИЗОЛЯЦИИ: ОПИСАТЕЛЬНОЕ ИССЛЕДОВАНИЕ

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Введение. Ночной сон — важный фактор сохранения здоровья и высокой работоспособности. В условиях стресса, например при длительной изоляции, его качество и длительность приобретают особое значение: проблемы со сном способны усиливать стрессовое состояние и ухудшать когнитивные способности. В таких условиях продолжительность сна становится решающим фактором, влияющим на самочувствие и продуктивность человека-оператора в последующий день. Однако ее роль в формировании процессов утренней активации изучена недостаточно.

Цель. Выявление особенностей двигательной активности во время ночного сна и вегетативной регуляции после утреннего пробуждения у лиц с различной продолжительностью сна в условиях длительного изоляционного эксперимента.

Материалы и методы. Исследование проводилось в рамках международного изоляционного эксперимента «SIRIUS-23/24» с участием 6 здоровых добровольцев (2 мужчин, 4 женщины, возраст 25–37 лет). По продолжительности сна участники были разделены на две группы: с коротким (< 7 ч; $n = 4$, 2 мужчин, 2 женщины, возраст 27–37 лет) и более длительным сном (> 7 ч; $n = 2$, 2 женщины, возраст 25 и 34 года). Ежемесячно осуществляли мониторинг двигательной активности во время сна методом актиграфии, регистрацию ЭКГ и анкетирование о характеристиках сна сразу после пробуждения. Анализировали показатели вариабельности сердечного ритма (SDNN, TP, VLF, SI, LF/HF), вегетативный индекс Кердо, а также продолжительность, эффективность сна и двигательную активность во время сна. Для оценки достоверности различий выделенных групп применялся непараметрический критерий Манна — Уитни.

Результаты. У участников группы с непродолжительным сном эффективность сна была ниже, а двигательная активность в ночные часы — выше. У участников этой же группы после пробуждения выявлено относительное снижение симпатических влияний: более низкие значения частоты сердечных сокращений (61,5 уд/мин, $p = 0,049$), индекса Кердо (-9,4 усл. ед., $p = 0,015$) и SI (48 усл. ед., $p = 0,04$); и усиление парасимпатической активности: более высокие значения SDNN (59,3 мс, $p = 0,005$) и TP (1994 мс², $p = 0,006$), что свидетельствует о нарушении утренней активации. В группе с более длительным сном, несмотря на лучшие показатели сна, зафиксированы более низкие значения мощности VLF после пробуждения по сравнению с группой с коротким сном ($p \leq 0,05$).

Выводы. В условиях длительной изоляции у некоторых членов экипажа отмечался короткий сон (< 7 ч), связанный с повышенной двигательной активностью во время ночного сна, снижением эффективности сна и ослаблением симпатической регуляции сердечного ритма после пробуждения. Полученные данные подчеркивают необходимость индивидуального подхода к оптимизации режима сна для поддержания работоспособности и здоровья в экстремальных условиях.

Ключевые слова: изоляция; сон; качество сна; продолжительность сна; вариабельность сердечного ритма; двигательная активность; изоляционный эксперимент SIRIUS-23/24; циркадианный ритм

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INTRODUCTION

It is well known that night sleep of normal duration and quality plays an important role in human life, contributing to recovery and the preservation of health in all its aspects — physical, cognitive, and emotional. Both shortened and excessively prolonged sleep have been shown to negatively affect the ability to concentrate and retain information, provoking increased irritability and reduced motivation [1]. Therefore, monitoring and

maintaining proper sleep rhythms are crucial measures for ensuring work safety and efficiency and improving quality of life.

In extreme conditions, assessing circadian rhythms is critical because a disrupted sleep schedule markedly elevates stress and fatigue levels. This not only impairs adaptation but also compromises health at both the individual and population scales. In such situations, reduced sleep quality can lead to deteriorated cognitive functions, lower work performance, and a higher

likelihood of errors among operators and specialists working in critical fields. In extreme conditions — such as space flights, isolation experiments simulating spaceflight environments, and long-term isolation during expeditions — a reduction in both sleep duration and quality, as well as disruptions in circadian rhythms, has been documented compared to control studies under normal conditions [2–7]. However, the question of individual sleep duration and its potential relationship with the post-awakening state remains largely unexplored.

Polysomnography is the gold standard for assessing nighttime sleep quality; however, given its complexity and high cost, simpler approaches are often required. In recent years, methods based on the analysis of motor activity and heart rate variability (HRV) have been increasingly applied to evaluate sleep quality [8].

Actigraphy is a widely used non-invasive method for the objective assessment of nighttime sleep duration and quality [8]. Motor activity during sleep is often associated with sleep segmentation and fragmentation, which underscores its value as a marker of sleep disturbances [9].

HRV analysis during nighttime sleep is primarily used in the study of circadian rhythms, as this non-invasive approach allows assessment of autonomic nervous system activity within the circadian framework. In athletes and individuals working in hazardous industries, overnight HRV monitoring serves as a tool for health status control and prevention of overtraining [10]. The method is of greatest diagnostic value immediately after awakening, since morning HRV parameters correlate with the body's readiness for daytime physical activity. Studies confirm that the highest HRV is observed in the morning hours, while it tends to decrease in the afternoon [11]. High HRV generally indicates the body's capacity to respond quickly and flexibly to external and internal stimuli, whereas reduced HRV is an independent risk factor for both health and work performance. [12]. Consequently, elevated HRV supports more effective adaptation to upcoming mental and physical tasks, enhancing productivity and resilience to fatigue development.

HRV is modulated by nocturnal sleep duration and quality. Research indicates that consolidated, restorative sleep promotes parasympathetic dominance, resulting in higher HRV indices as a marker of healthy autonomic balance. [13]. Shorter sleep duration is typically associated with lower HRV, indicating a potential link between insufficient sleep and reduced autonomic nervous system function [14]. Conversely, sufficiently long sleep duration may be associated with higher HRV [15]. However, some authors argue that both excessively short and excessively long sleep durations can have a negative impact on autonomic nervous system function [16].

It is important to note that the combined use of HRV indicators and motor activity data to determine sleep

stages significantly improves classification accuracy and sensitivity [17]. It has also been demonstrated that the analysis of heart rate, respiratory rate, and movement parameters obtained via ballistocardiography outperforms actigraphy in terms of sleep state detection accuracy [18]. Although the combined analysis of motor activity and HRV significantly expands the possibilities for assessing nighttime sleep quality [19], very few studies of this kind have been published to date.

We hypothesize that reduced nighttime sleep duration is a factor altering its qualitative characteristics, including changes in motor activity, which may indirectly indicate a decrease in sleep depth. These alterations may not be confined to the nighttime period but could extend into the early morning, affecting autonomic balance and the level of post-awakening activation.

The aim of the study is to identify the specific features of motor activity during nighttime sleep and autonomic regulation after morning awakening in individuals with different sleep durations under conditions of a long-term isolation experiment.

MATERIALS AND METHODS

The experiment was carried out within the framework of the international SIRIUS-23/24 project, which involved a one-year isolation period. Six volunteer test subjects participated — two men and four women, aged 25–37 years. All participants underwent an in-depth medical examination, were confirmed to be in good health, and were cleared to take part in the study.

Motor activity was recorded once at the end of each isolation month using a non-contact method over the course of a night. The Cardioson device (Medical Computer Systems, Russia), comprising a plate with an integrated accelerometric sensor, was positioned beneath each participant's mattress at the level of the sternum. Based on the initial accelerometric signal (sampling frequency — 500 Hz), segments of motor activity were identified when the threshold value calculated by an adaptive algorithm was exceeded. The number and duration of movements lasting at least 1 s were computed for every 5-min interval using custom software developed at the Institute of Biomedical Problems of the RAS (IBMP RAS) [20].

Immediately after the participants' awakening, monitoring of the cardiovascular system and its autonomic regulation was carried out. Upon awakening, participants performed self-measurements of blood pressure (BP) and heart rate (HR). This was followed by a 5-minute ECG recording using the MH-01 wireless cardioregister (BORSAM Biomedical Instruments, China). Finally, via the Stress-Control hardware-software complex (IBMP RAS), subjects completed a questionnaire regarding their sleep-wake cycle characteristics, including items on nocturnal sleep quality and daytime sleepiness.

The study analysed cardiovascular and autonomic recordings alongside morning questionnaire responses regarding sleep quality following nights with monitored motor activity. In total, 60 records were obtained from 6 participants over 12 months. Some motor activity records were excluded due to technical issues.

Based on the BP and HR measurements, the Kerdo Vegetative Index (KVI) was calculated using the formula: $KVI = (1 - (BP / HR)) \times 100$. During electrocardiogram (ECG) recording, the durations of a consecutive series of RR intervals were analysed, and HRV parameters were evaluated in accordance with international and Russian standards [21]. The following HRV parameters were analysed:

- RMSSD — root mean square of successive differences (between successive normal RR intervals);
- HF — spectral power of heart rate oscillations in the high-frequency range (0.15–0.4 Hz);
- LF — spectral power of heart rate oscillations in the low-frequency range (0.04–0.15 Hz);
- VLF — spectral power of heart rate oscillations in the very low-frequency range (0.003–0.04 Hz);
- LF/HF — the ratio of low-frequency to high-frequency spectral components;
- SDNN — standard deviation of NN intervals (all intervals between successive normal heartbeats);
- SI — the stress index reflecting the level of tension in adaptive and protective systems;
- TP — the total power, i.e. the sum of power values in the HF, LF, and VLF bands.

In the questionnaire, participants reported bedtime, sleep onset latency, duration of nocturnal awakenings, and time of morning awakening. Total sleep time was calculated as the difference between time in bed and the sum of sleep onset latency and the total duration of

nocturnal awakenings. Sleep efficiency (SE) was computed as the ratio of total sleep time to time in bed [22].

Statistical analysis was performed using Statistica 10.0 software (StatSoft, USA). Numerical data are presented as medians and percentiles: M_e (P25; P75). The non-parametric Mann–Whitney test was applied to compare the groups.

RESULTS

Based on the questionnaire results, the crew members were divided by an expert panel into two groups according to nighttime sleep duration: four individuals who, on average, slept less than 7 h (6.5 ± 0.2 h), and two individuals who slept more than 7 h (7.5 ± 0.3 h).

Data from the monthly questionnaire survey on nighttime sleep characteristics and daily routine during the 12-month isolation period were analysed for each crew member (Table 1). On average, such parameters as sleep duration, sleep onset latency, and duration of nocturnal awakenings did not exceed the normal reference ranges: 6–10 h for sleep duration, up to 30 min for sleep onset latency, and up to 15 min for the duration of nocturnal awakenings [23].

The reduced nighttime sleep duration in the first group was mainly due to a later bedtime and prolonged sleep onset latency. Additionally, the sleep efficiency index (SEI) was significantly lower in the group with shorter nighttime sleep.

Analysis of nocturnal motor activity revealed significantly lower movement levels in the long-sleep group compared to short-sleepers ($p < 0.05$; see Table 2), suggesting superior sleep quality and stability in this cohort. Analysis of parameters reflecting cardiovascular homeostasis and autonomic regulation in the groups

Table 1. Sleep characteristics of the SIRIUS-23/24 crew members based on the “sleep–wake” questionnaire

Crew member sequence number	Bedtime (hh:mm)	Wake-up time (hh:mm)	Sleep onset latency (min)	Duration of nocturnal awakening (min)	Time in bed (h)	Sleep duration (h)	Sleep Efficiency Index (SEI), %
Group 1: sleep duration < 7 h							
1	24:00 ± 00:12	6:10 ± 0:00	31.30 ± 0.00	2.30 ± 0.48	7.10 ± 0.09	6.36 ± 0.12	89.6 ± 0.02
2	23:36 ± 00:15	6:53 ± 00:07	19.30 ± 7.48	2.00 ± 0.48	7.18 ± 0.14	6.56 ± 0.13	91.4 ± 0.00
3	23:45 ± 00:13	7:00 ± 0:07	25.30 ± 7.11	3.30 ± 0.00	7.15 ± 0.13	6.46 ± 0.13	90.3 ± 0.00
4	24:00 ± 00:07	7:10 ± 0:07	15.00 ± 7.48	1.30 ± 0.30	7.08 ± 0.08	6.51 ± 0.07	91.9 ± 0.00
Group 2: sleep duration > 7 h							
5	23:36 ± 00:07	7:00 ± 0:07	15.00 ± 7.48	0.00 ± 0.00	7.25 ± 0.09	7.10 ± 0.13	97.9 ± 0.03
6	23:19 ± 00:09	7:26 ± 0:00	16.30 ± 0.00	4.30 ± 0.00	8.07 ± 0.12	7.46 ± 0.12	92.4 ± 0.00

Table prepared by the authors using their own data
Note. Number of measurements (n) per crew member — 10.

Table 2. Nighttime motor activity and cardiovascular autonomic control parameters in SIRIUS-23/24 crew members

Parameters	Group 1 (sleep < 7 h) <i>n</i> = 40	Group 2 (sleep > 7 h) <i>n</i> = 20	<i>p</i> -value (Mann–Whitney <i>U</i> test), <i>p</i>
Number of motor activity episodes per 5-min interval	1.55 (1.15; 2.14)	0.89 (0.71; 1.36)	0.001
Heart rate, bpm	61.50 (59; 66.25)	68 (55; 78.50)	0.049
Kerdo vegetative index, arbitrary units (a.u.)	-9.40 (-34.50; -1.87)	12.10 (-27.25; 21.50)	0.015
RMSSD, ms	39.70 (33.25; 47.25)	40.20 (29.20; 45.30)	1.000
HF, ms ²	529 (206.50; 766.50)	382 (240; 699)	0.878
LF, ms ²	776 (472.50; 1176.30)	562 (411; 836)	0.140
VLF, ms ²	547 (431; 1035)	483 (326; 526)	0.037
LF/HF, arbitrary units (a.u.)	1.64 (0.77; 7.75)	1.68 (0.75; 2.86)	0.581
SDNN, ms	59.3 (50.40; 72.35)	48 (44. 30; 56.80)	0.005
SI, arbitrary units (a.u.)	48 (31; 67.50)	72 (59; 94)	0.004
TP, ms ²	1994 (1657.50; 2749.50)	1599 (1202; 1925)	0.006

Table prepared by the authors using their own data

Note. RMSSD — root mean square of successive differences; HF — spectral power of heart rate oscillations in the high-frequency range (0.15–0.4 Hz); LF — spectral power of heart rate oscillations in the low-frequency range (0.04–0.15 Hz); VLF — spectral power of heart rate oscillations in the very low-frequency range (0.003–0.04 Hz); LF/HF — ratio of low-frequency to high-frequency spectral components; SDNN — standard deviation of NN intervals; SI — stress index; TP — total power values in the HF, LF, and VLF bands; *n* — number of measurements; * — *p* < 0.05 — *p*-value (Groups 1 vs. 2, Mann–Whitney *U* test); values are presented as medians with percentiles *M*_e (P25; P75); significant differences between Groups 1 and 2 (Mann–Whitney *U* test) are indicated in italics (*p* < 0.05).

stratified by nighttime sleep duration showed that these groups differed significantly in the following indicators: VLF, SDNN, Kerdo index, SI, and TP (Table 2).

Crew members with longer sleep duration demonstrated significantly higher resting heart rates and Kerdo index values in the morning (*p* < 0.05), indicating a relative predominance of sympathetic regulation within their cardiovascular homeostasis. The Kerdo index value in the group with sleep duration less than 7 h was significantly lower compared to the group with sleep duration more than 7 h, by 17.65 arbitrary units. Considering that the Kerdo index is an indirect indicator of vagosympathetic balance, the observed changes suggest greater hemodynamic efficiency and improved recovery and energy accumulation in the morning in crew members with sleep duration less than 7 h.

Table 2 also summarizes HRV metrics that differed significantly between the short-sleep and long-sleep cohorts (*p* < 0.05). These parameters characterize the overall effect of regulatory activity and the body's adaptive reserves (SDNN, TP), as well as the activity of the sympathetic division of the autonomic nervous system (SI), and the degree of central nervous system involvement in autonomic regulation, along with the status of humoral and metabolic regulatory

mechanisms (VLF). In the morning, crew members who slept less than 7 h showed increased parasympathetic and decreased sympathetic influences on heart rate. The enhanced parasympathetic activity is supported by changes in HRV parameters such as SDNN and TP. The SDNN value, which reflects the standard deviation of all NN intervals and the overall effect of autonomic regulation of circulation, averaged 62.31 ms in the less than 7 h sleep group and 50.97 ms in the group with longer sleep duration. Lower sympathetic nervous system activity in the morning, observed in participants with shorter sleep duration based on blood pressure measurements (Kerdo index), is supported by the comparison of the SI values between the groups. The mean SI value after awakening in the less than 7 h sleep group was 53.35 arbitrary units, which is at the border of the physiological norm [21] and may indicate reduced activity of stress-response systems during the morning period.

VLF power was approximately 50% lower in Group 2 than in Group 1, consistent with reduced energy-metabolic activity in the short-sleep cohort. This may indicate a reduced level of metabolic and energy processes, as well as the insufficiency of even a longer sleep duration in Group 2.

DISCUSSION

Findings from the SIRIUS-23/24 experiment revealed heterogeneous sleep requirements among individuals during 12 months of isolation, as reflected by variable sleep durations. Based on nightly sleep duration, the cohort was divided into two subgroups: short-sleepers ($n = 4$; mean duration: 6 h 48 min) and long-sleepers ($n = 2$; mean duration: ~7 h 18 min). Notably, the short-sleep group showed prolonged sleep onset latency, suggesting a possible impairment of the sleep's restorative capacity.

Sleep duration was found to be a significant differentiating factor between the groups: it was associated with distinct patterns of morning autonomic activity (sympathetic and parasympathetic tone) and with the level of motor activity during sleep.

It is well established that the diurnal rhythmicity of the parasympathetic and sympathetic branches of the autonomic nervous system is linked to central circadian rhythms. The transition from sleep to wakefulness is accompanied by activation of the sympathetic nervous system, which aligns with the peak cortisol levels observed in the daily cycle [24]. The observed attenuation of sympathetic influences on heart rate and hemodynamic regulation (Kerdo index) in the morning in the less than 7 h sleep group may indicate a disrupted circadian rhythm and impaired morning activation of stress-response systems. The observed alterations in nocturnal sleep in this group — prolonged sleep onset latency, higher motor activity during sleep, and reduced sleep efficiency index — may represent the primary mechanism underlying the detected shifts in the sleep–wake cycle.

At the same time, in Group 2, despite the longer nocturnal sleep duration and higher sleep efficiency, reduced VLF spectral power values indicate attenuated heart rate fluctuations in the very low frequency

range. These fluctuations are associated, among other factors, with hypothalamic-pituitary-adrenal axis activity, the body's energy-metabolic resources, and as-thenization [25]. This may indicate impaired adaptive capacity and an increased subjective need for sleep. In this context, the longer sleep duration may represent a compensatory response to the extreme conditions of prolonged isolation, which are challenging for the human body.

CONCLUSIONS

The SIRIUS-23/24 12-month isolation study revealed marked inter-individual variability in sleep duration among crew members. In some participants, sleep duration of less than 7 h was linked to elevated nocturnal motor activity, lower sleep efficiency, and relatively diminished sympathetic regulation of heart rate and cardiovascular homeostasis in the post-awakening period. These patterns may reflect altered autonomic adaptation under prolonged isolation. This suggests a disruption of circadian rhythmicity, a potential impairment of the body's adaptive capacity within the sleep–wake cycle, and difficulties in sustaining goal-directed activity in the morning hours. The study findings revealed signs of circadian rhythm disruption and specific compensatory responses in participants of Groups 1 and 2 under the extreme conditions of the isolation experiment. It is hypothesized that a greater reduction in nocturnal sleep to 6 h or less (partial sleep deprivation) may induce more pronounced alterations in autonomic balance after awakening, which in turn may contribute to reduced performance and the development of sleep inertia. The obtained data emphasize the importance of an individualized approach to organizing the sleep–wake schedule under prolonged isolation conditions and highlight the need for further research to develop effective measures for maintaining crew health and performance.

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