

Assessment of the dependence of heart rate variability on sleep patterns in adolescents

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ABSTRACT

Background: Sleep disturbances and irregular sleep schedules are increasingly recognized as important risk factors for autonomic nervous system function and cardiovascular health in adolescents. Heart rate variability (HRV) is a sensitive, noninvasive marker of autonomic regulation and cardiovascular adaptive capacity. **Objective:** To investigate the association between sleep schedule adherence and HRV parameters in adolescents. **Methods:** This cross-sectional observational study included 200 schoolchildren aged 15–16 years in grades 9–10 in Ust-Kamenogorsk, Kazakhstan. Sleep patterns and chronotypes were assessed using the Horne–Östberg Morningness–Eveningness Questionnaire. Based on bedtime, participants were classified into a regular sleep schedule group ($n = 147$) and an irregular sleep schedule group ($n = 53$). Heart rate variability was assessed with the VNS-Spectrum system (Neurosoft, Russia) under resting conditions and during an active orthostatic test. Time-domain, frequency-domain, and geometric HRV parameters were analyzed. Statistical analyses were conducted using IBM SPSS Statistics 25.0. **Results:** Adolescents with a regular sleep schedule had significantly lower heart rate and higher RRNN, SDNN, RMSSD, pNN50, total power (TP), and high-frequency (HF) values than those with an irregular sleep schedule (all $p < 0.001$). The LF/HF ratio and stress index (SI) were also significantly lower, indicating predominant parasympathetic activity and more effective autonomic regulation. During the orthostatic test, both groups showed physiological sympathetic activation; however, adolescents with a regular sleep schedule maintained significantly higher HRV indices, reflecting greater cardiovascular adaptive capacity. In contrast, adolescents with an irregular sleep schedule showed reduced HRV, greater sympathetic predominance, elevated stress index, and diminished autonomic functional reserves. **Conclusions:** A regular sleep schedule is associated with more favorable autonomic regulation, higher HRV, and greater cardiovascular adaptive capacity in adolescents. In contrast, irregular sleep patterns are associated with sympathetic predominance, reduced vagal modulation, and diminished cardiovascular functional reserve. These findings underscore the importance of sleep hygiene interventions and healthy sleep habits as preventive strategies for preserving cardiovascular health in adolescents.

Keywords: Adolescents health, Sleep schedule, Sleep hygiene, Heart rate variability, HRV, Autonomic nervous system, Parasympathetic activity, Sympathetic activity, Cardiovascular adaptation, Chronotype, Orthostatic test.

Article type: Research Article.

INTRODUCTION

Children and adolescents are particularly sensitive to both external and internal environmental influences during growth and physiological development. Among these factors, sleep patterns are one of the most critical determinants of health. Sleep deprivation and disturbances have become major global public health concerns. This

trend is driven not only by digitalization and the widespread use of social media but also by multiple factors that interfere with nighttime sleep, including light pollution, noise pollution, air pollution, social desynchronization, and psycho-emotional stress. In addition, prolonged evening use of electronic devices, combined with increased exposure to urban light and noise, has been shown to impair sleep quality. Previous studies have demonstrated that screen use before bedtime shortens sleep duration and significantly impairs sleep quality (Silva *et al.* 2022; Brosnan *et al.* 2024). Numerous studies have examined the effects of artificial light at night (ALAN) on the cardiovascular system in both humans and experimental animals. An extensive review of the literature shows that nighttime light exposure reduces the normal circadian variability of blood pressure and heart rate. In diurnal species, including humans, exposure to artificial light at night increases cardiovascular activity during the biological night, whereas the opposite effect has been observed in nocturnal animals. These physiological responses are primarily mediated by the autonomic nervous system and are associated with circadian disruption. In addition, ALAN acts as a chronic stressor by altering glucocorticoid secretion and glucose metabolism, which may lead to molecular changes in the heart and blood vessels. Together, these findings suggest that nighttime light exposure disrupts normal circadian physiological homeostasis and may increase the long-term risk of cardiovascular disease. ALAN also reduces the circadian variability of blood pressure and heart rate, disturbs circadian rhythmicity, elevates nocturnal blood pressure in older adults, and increases the risk of atherosclerosis (Obayashi *et al.* 2014; Obayashi *et al.* 2015; Molcan *et al.* 2024). Several studies have also reported that exposure to light during sleep increases heart rate, impairs cardiometabolic function, and contributes to the development of overweight, obesity, and type 2 diabetes mellitus (Mason *et al.* 2022; Kim *et al.* 2023). In addition to artificial light, a growing body of evidence indicates that environmental noise adversely affects sleep quality. Numerous studies have examined the mechanisms by which environmental noise, particularly from road traffic, aircraft, and railway transport, affects the cardiovascular system. Environmental noise has been identified as a chronic stressor capable of activating both the sympathetic nervous system and the hypothalamic–pituitary–adrenal (HPA) axis, resulting in increased secretion of stress hormones. Consequently, arterial blood pressure increases, endothelial function deteriorates, and oxidative stress and inflammatory processes are enhanced. Epidemiological studies have consistently shown that chronic exposure to environmental noise is associated with an increased risk of arterial hypertension, coronary heart disease, myocardial infarction, and stroke. Accordingly, environmental noise is recognized as an important modifiable risk factor for cardiovascular disease, underscoring the need for effective public health measures to reduce noise exposure (Münzel *et al.* 2021). Münzel *et al.* comprehensively investigated the effects of environmental noise on human health, with particular emphasis on the cardiovascular system. The authors identified environmental noise as a chronic stressor that activates both the sympathetic nervous system and the endocrine system, resulting in elevated stress hormone levels. Consequently, endothelial function is impaired, while oxidative stress and inflammatory processes are enhanced. Based on epidemiological evidence, the authors demonstrated that long-term exposure to environmental noise is associated with an increased risk of arterial hypertension, coronary heart disease, myocardial infarction, and stroke. Furthermore, noise-induced sleep disturbance is considered one of the principal mechanisms through which environmental noise exerts adverse cardiovascular effects (Münzel *et al.* 2018). Babisch presented the results of a meta-analysis evaluating the association between road traffic noise and coronary heart disease (CHD). By synthesizing data from previously published epidemiological studies, the author demonstrated a positive dose–response relationship between increasing levels of road traffic noise and the risk of CHD. Specifically, each 10 dB increase in the average daily noise level was associated with an approximately 8% increase in the risk of coronary heart disease. The authors suggested that these effects are mediated through chronic stress responses, increased sympathetic nervous system activity, elevated blood pressure, and sleep disturbances. Overall, the study provides strong evidence that environmental noise represents an important modifiable risk factor for cardiovascular disease (Babisch 2014). In a cohort study conducted by Sørensen *et al.*, the association between long-term exposure to road traffic noise and the risk of myocardial infarction was investigated. The study followed a large cohort of adult residents in Denmark over several years, during which road traffic noise levels at participants' residential addresses were estimated. The findings demonstrated that higher levels of road traffic noise were associated with an increased incidence of myocardial infarction, with the association being particularly pronounced among older adults. The authors concluded that the cardiovascular effects of environmental noise are mediated through sleep disturbances, enhanced stress responses, activation of the sympathetic nervous system, and elevated arterial blood pressure. These findings further support the role of environmental noise as a significant risk factor for cardiovascular disease

(Sørensen *et al.* 2012). Under conditions of rapid urbanization, the increasing adoption of a "nighttime lifestyle," widespread exposure to artificial light, and extensive evening use of electronic devices contribute to delayed sleep onset among children and adolescents, thereby disrupting circadian rhythms and promoting social desynchronization. Evidence from systematic reviews indicates that delayed sleep timing and social jetlag are highly prevalent among children and adolescents and are associated with adverse health outcomes. Furthermore, frequent use of screen-based media is directly associated with increased social jetlag and impaired sleep patterns (Jean-Philippe Chaput *et al.* 2022; Wendy *et al.* 2024). Collectively, these environmental and behavioral factors adversely affect sleep quality and may, in turn, impair psychophysiological health. Given the high sensitivity of the cardiovascular system to sleep quality, these findings suggest that the burden of cardiovascular diseases may increasingly affect younger populations in the future. In this context, the findings of the present study contribute to United Nations Sustainable Development Goal 3 (SDG 3): Good Health and Well-being, as they provide evidence to support the promotion of healthy sleep habits, the prevention of non-communicable diseases, and the improvement of health and well-being among young people.

MATERIALS AND METHODS

This cross-sectional observational study included 200 students aged 15–16 years enrolled in grades 9 and 10 at a general secondary school in Ust-Kamenogorsk, Kazakhstan, where the geographical time corresponds to the official administrative time. Participants were selected by simple random sampling. Sleep–wake characteristics and chronotypes were assessed using the Horne–Östberg Morningness–Eveningness Questionnaire. Face-to-face assessments were conducted at the school in the morning (09:30–12:00). Based on the questionnaire results, participants were classified into two groups: those with an appropriate sleep schedule and those without one. Heart rate variability (HRV) analysis was subsequently performed in both groups.

Heart Rate Variability (HRV) Assessment. HRV was evaluated in all participants using the VNS-Spectrum system (Neurosoft, Russia) in accordance with the standard protocol. Recordings were obtained under two conditions: in the supine resting position (baseline) and during an active orthostatic test in the standing position. Short-term HRV recordings were analyzed because these parameters are sensitive to external influences, including psycho-emotional stress, physical exertion, changes in body position, and other physiological factors. To minimize external interference, data acquisition and preliminary processing were performed in real time under standardized conditions in specially equipped, quiet rooms.

Statistical analysis

Statistical analyses were performed using Microsoft Excel (including the Data Analysis ToolPak add-in) and IBM SPSS Statistics version 25.0 (IBM Corp., Armonk, NY, USA). Descriptive statistics were calculated to characterize the study sample. Continuous variables were reported as the mean $\pm$ standard deviation (SD) and, when appropriate, as the median. Categorical variables were presented as frequencies and percentages. Between-group comparisons of categorical variables were conducted using the chi-square (χ^2) test. For continuous variables, the independent-samples Student's *t*-test was used for normally distributed data, whereas the Mann–Whitney U test was applied for non-normally distributed data.

RESULTS

According to the Horne–Östberg questionnaire, most students (57.5%, $n = 115$) reported going to bed between 21:30 and 00:15, which can be considered a relatively appropriate bedtime for school-aged adolescents. However, 26.5% ($n = 53$) reported falling asleep after 00:15, including 16.0% ($n = 32$) between 00:15 and 01:30, and 10.5% ($n = 21$) between 01:30 and 03:00. Such delayed sleep timing may create a mismatch between adolescents' biological rhythms and the school schedule. By contrast, only a small proportion of students had an early bedtime: 4.0% ($n = 8$) went to bed between 20:00 and 20:45, and 12.0% ($n = 24$) between 20:45 and 21:30. Overall, only 16.0% ($n = 32$) of the students went to bed before 21:30. Regarding chronotype distribution, most students were classified as having an intermediate chronotype (76.0%, $n = 152$). This group is generally well adapted to daytime activities, and its biological rhythms are relatively well aligned with the conventional school schedule. The evening chronotype was identified in 16.0% ($n = 32$) of the students. Adolescents in this group are typically more active in the evening, go to bed later, and frequently have difficulty waking up early in the morning. Consequently, early school start times may impose additional physiological and social burdens on these adolescents. Only 8.0% of the participants ($n = 16$) were classified as having a morning chronotype. These students usually go to bed and wake up earlier, and therefore are best adapted to the school's administrative schedule. Compared with adolescents

from Atyrau, Kazakhstan, where the difference between geographical time and official administrative time reaches up to 1.5 hours, the chronotype distribution in the present study was much more favorable. In the Atyrau cohort, the distribution was shifted toward the intermediate and evening chronotypes: only 3.8% of adolescents were morning types, whereas 69.8% and 26.4% were classified as intermediate and evening types, respectively (Kalekeshov *et al.* 2025). From the perspective of alignment between social and administrative time, the predominance of the intermediate chronotype among the participants suggests that the current school schedule is generally appropriate for most students. Nevertheless, the finding that approximately one in six students had an evening ("owl") chronotype highlights the need to consider chronotype-related differences when organizing the educational process. Therefore, improving sleep hygiene among school-aged children and adapting school schedules to circadian characteristics should be regarded as important public health priorities. Based on the Horne–Östberg questionnaire, students with an appropriate sleep schedule were grouped. This group included students who reported going to bed between 20:00 and 20:45 ($n = 8$) and between 20:45 and 21:30 ($n = 24$), as well as those who reported falling asleep between 21:30 and 00:15 (57.5%, $n = 115$). These participants were combined into a single group for subsequent analyses (Fig. 1).

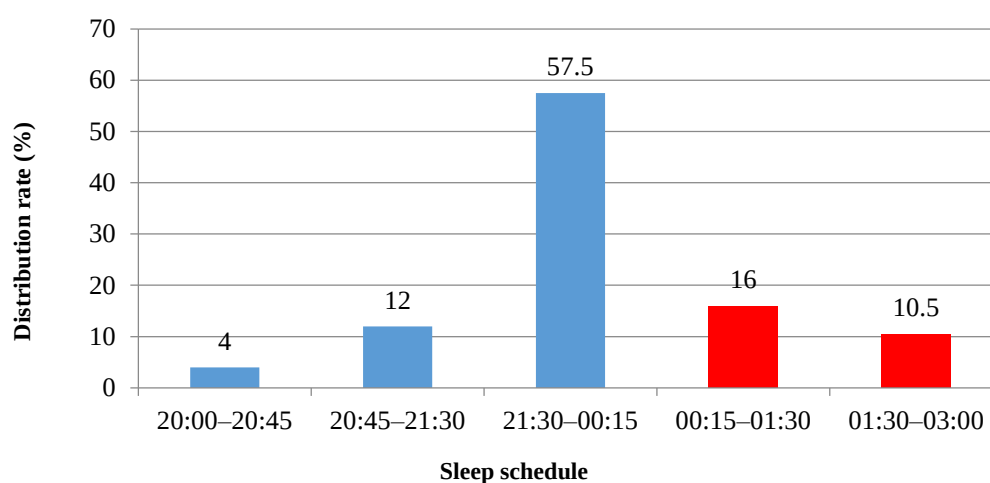


Fig. 1. Percentage distribution of adolescents according to sleep schedule (%).

This bedtime interval was considered relatively appropriate for school-aged adolescents. Overall, 147 students (73.5%) were classified as having an appropriate sleep schedule. In contrast, participants who reported going to bed between 00:15 and 01:30 (16.0%, $n = 32$) and those falling asleep between 01:30 and 03:00 (10.5%, $n = 21$) were classified as having an irregular sleep schedule, comprising 53 participants (26.5%) of the total sample. Such delayed sleep timing may contribute to a misalignment between adolescents' biological rhythms and the school's administrative schedule, thereby promoting circadian misalignment. Subsequently, heart rate variability (HRV) was assessed in both groups. In the regular sleep schedule group, the resting heart rate (HR) was 70.50 ± 0.45 beats min^{-1} , whereas RRNN, SDNN, RMSSD, and pNN50 values were relatively elevated. These findings suggest predominant parasympathetic activity and effective autonomic regulation under resting conditions. During the orthostatic test, HR increased as expected under normal physiological conditions, while RRNN, SDNN, RMSSD, and pNN50 decreased significantly (all $p < 0.001$). In addition, total power (TP), high-frequency (HF), and very-low-frequency (VLF) components decreased, whereas the LF/HF ratio increased. These changes reflect an appropriate adaptive response to postural change and indicate activation of the sympathetic branch of the autonomic nervous system. Analysis of the histogram-derived parameters showed a marked increase in the stress index (SI); although the value remained within the physiological range of adaptive responses. The decrease in the ell_S parameter on the Poincaré plot indicated reduced heart rate variability during orthostatic loading, while the overall HRV remained relatively high. In adolescents with an irregular sleep schedule, resting HRV analysis revealed a higher heart rate and significantly lower RRNN, SDNN, RMSSD, and pNN50 values compared with the regular sleep schedule group. These findings indicate reduced parasympathetic activity and a relative predominance of sympathetic autonomic modulation. Although sympathetic activation increased during the orthostatic test in both groups, the attenuation in time-domain HRV parameters was subsequently more pronounced in adolescents with an irregular sleep schedule. The pronounced reductions in RMSSD and pNN50 indicate impaired vagal modulation and diminished parasympathetic control. Frequency-domain analysis showed

that, although the decrease in total power (TP) did not reach statistical significance, the marked reduction in the HF component, together with an elevated LF/HF ratio, reflected sympathetic predominance. In addition, the increased stress index (SI) indicated greater functional strain on the autonomic regulatory systems.

Table 1. Comparison of the main heart rate variability (HRV) parameters between adolescents with regular and irregular sleep schedules.

Parameter	Regular sleep schedule group, n = 53 (Resting condition) n = 147	Regular sleep schedule group, n = 53 (Orthostatic) n = 147	Irregular sleep schedule group, n = 53 (Resting condition) n = 53	Irregular sleep schedule group, n = 53 (Orthostatic) n = 53
HR (bpm)	70.50 ± 0.45	94.80 ± 0.78***	82.79 ± 1.22	104.62 ± 1.60***
RRNN (ms)	860.97 ± 5.35	646.66 ± 5.81***	739.85 ± 10.03	586.62 ± 8.36***
SDNN (ms)	67.74 ± 1.16	42.73 ± 1.37***	39.68 ± 1.46	33.64 ± 1.78**
RMSSD (ms)	67.07 ± 1.61	22.03 ± 1.45***	35.11 ± 2.16	15.92 ± 1.21***
pNN50 (%)	40.92 ± 1.27	6.39 ± 1.18***	14.76 ± 1.90	2.40 ± 0.61***
TP (ms ²)	4505.82 ± 209.29	2079.30 ± 124.81***	1497.96 ± 97.49	1292.40 ± 131.95
LF (ms ²)	1374.65 ± 96.74	908.24 ± 48.67***	402.77 ± 33.60	633.43 ± 75.35**
HF (ms ²)	1774.53 ± 102.23	375.27 ± 65.91***	486.92 ± 44.31	170.28 ± 21.29***
LF/HF	0.85 ± 0.03	6.65 ± 0.39***	1.18 ± 0.12	4.83 ± 0.24***
SI	62.93 ± 2.03	271.81 ± 22.92***	196.06 ± 24.30	324.63 ± 29.82**

Note: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$ (Comparison of HRV parameters under resting and orthostatic conditions).

The data presented in Table 1 demonstrated statistically significant differences between the two groups across all major HRV parameters. Adolescents with a regular sleep schedule exhibited a lower heart rate (HR) and a higher mean RR interval (RRNN) than those with an irregular sleep schedule. In addition, SDNN, RMSSD, and pNN50 values were significantly higher in the regular sleep schedule group (all $p < 0.001$), indicating greater stability of sinus rhythm and enhanced vagal modulation of cardiac activity. Spectral analysis further demonstrated that total power (TP) and the high-frequency (HF) component were markedly higher in adolescents with a regular sleep schedule, whereas the LF/HF ratio was significantly lower. These findings suggest a more favourable balance between the sympathetic and parasympathetic regulation of the autonomic nervous system activity. Conversely, adolescents with an irregular sleep schedule demonstrated lower overall heart rate variability and a higher stress index (SI), indicating diminished cardiovascular functional reserves and increased strain on autonomic regulatory mechanisms.

Table 2. Comparison of heart rate variability (HRV) parameters between the two groups during the orthostatic test.

Parameter	Regular sleep schedule group (n = 147)	Irregular sleep schedule group (n = 53)	p-value
HR (bpm)	70.50 ± 0.45	82.79 ± 1.22	$p < 0.001$
RRNN (ms)	860.97 ± 5.35	739.85 ± 10.03	$p < 0.001$
SDNN (ms)	67.74 ± 1.16	39.68 ± 1.46	$p < 0.001$
RMSSD (ms)	67.07 ± 1.61	35.11 ± 2.16	$p < 0.001$
pNN50 (%)	40.92 ± 1.27	14.76 ± 1.90	$p < 0.001$
TP (ms ²)	4505.82 ± 209.29	1497.96 ± 97.49	$p < 0.001$
HF (ms ²)	1774.53 ± 102.23	486.92 ± 44.31	$p < 0.001$
LF/HF	0.85 ± 0.03	1.18 ± 0.12	$p < 0.01$

Values are presented as mean $\pm$ standard error ($M \pm m$). Between-group comparisons were performed using Welch's independent t-test. $p < 0.05$ – statistically significant; $p < 0.01$ – highly significant; $p < 0.001$ – very highly significant. The orthostatic test revealed clear intergroup differences in adaptive capacity. In adolescents with a regular sleep schedule, heart rate (HR) increased in response to orthostatic loading, as expected under normal physiological conditions. However, RRNN, SDNN, and RMSSD remained relatively elevated, indicating preserved autonomic regulation and sufficient functional reserves. By contrast, adolescents with an irregular sleep schedule exhibited a more pronounced increase in HR, while SDNN, RMSSD, and pNN50 remained substantially lower. In addition, the marked reductions in total power (TP) and the high-frequency (HF) component suggested impaired autonomic regulation and attenuated parasympathetic modulation. Although the LF/HF ratio increased in both groups during the orthostatic test, adolescents with an irregular sleep schedule showed significantly higher stress index (SI) values, indicating excessive sympathetic activation and greater strain on autonomic regulatory mechanisms. Overall, the findings suggest that adolescents with a regular sleep schedule demonstrate greater cardiovascular adaptive capacity, whereas those with an irregular sleep schedule exhibit reduced autonomic functional reserves and diminished cardiovascular adaptability.

Fig. 2 presents the heart rate variability (HRV) rhythmograms of an adolescent with a regular sleep schedule under resting and orthostatic conditions.

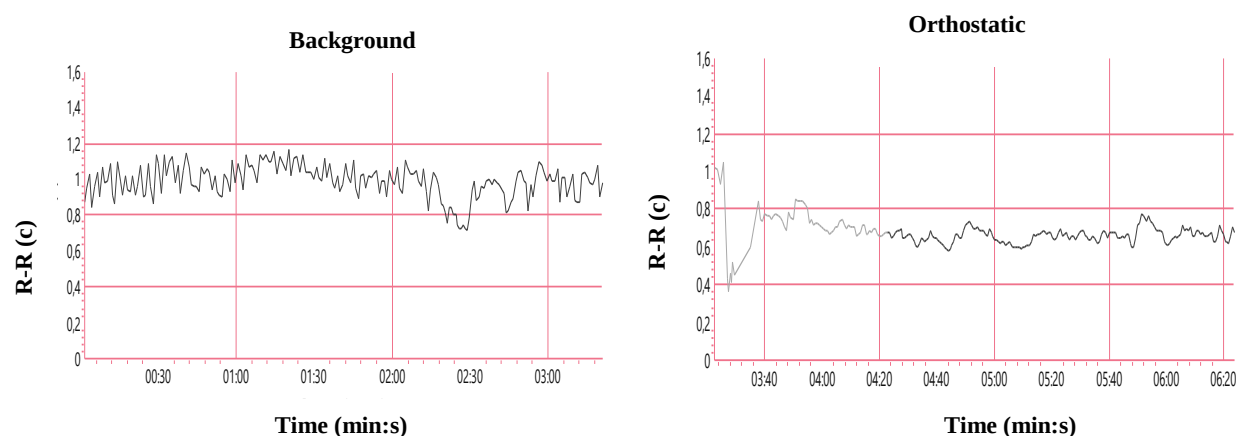


Fig. 2. Heart rate variability (HRV) rhythmograms of Patient A recorded under resting and orthostatic conditions.

The rhythmograms show a uniform distribution of R–R intervals with pronounced physiological fluctuations, indicating a high level of HRV. The stable pattern reflects normal sinoatrial node function and efficient autonomic regulation of cardiac rhythm. The natural variability of the R–R intervals suggests predominant parasympathetic activity. Collectively, these findings indicate well-preserved cardiovascular functional reserves and adequate adaptive response to external stimuli.

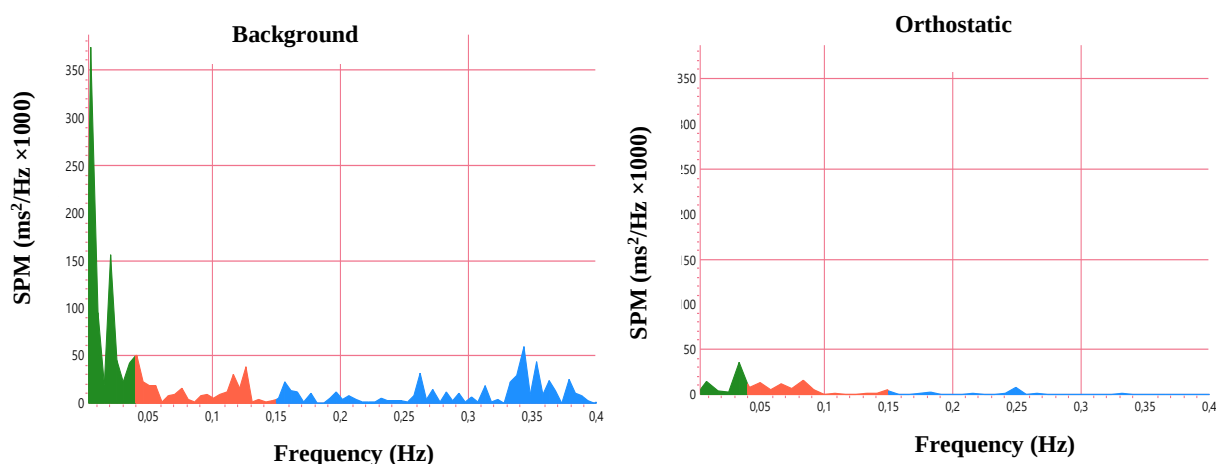


Fig. 3. HRV spectrograms of Patient A recorded under resting and orthostatic conditions.

The spectrogram demonstrated a clear predominance of the high-frequency (HF) component, indicating strong vagal modulation of cardiac activity and preserved physiological respiratory sinus arrhythmia (Fig. 3). The relatively high total power (TP) of the HRV spectrum reflects the preserved activity across all components of autonomic regulation. In addition, the LF/HF ratio remained within the physiological range, suggesting a balanced interaction between the sympathetic and parasympathetic divisions of the autonomic nervous system. The histogram showed a broad and symmetrical distribution of R–R intervals, indicating high heart rate variability (Fig. 4). The wide spread of the variation series reflects substantial beat-to-beat fluctuations, which are characteristic of well-preserved autonomic regulation. The low stress index (SI) suggests minimal functional strain on the autonomic regulatory systems and indicates that cardiac activity is maintained in an energy-efficient physiological state. Overall, these findings are consistent with high adaptive capacity and well-preserved cardiovascular functional reserves.

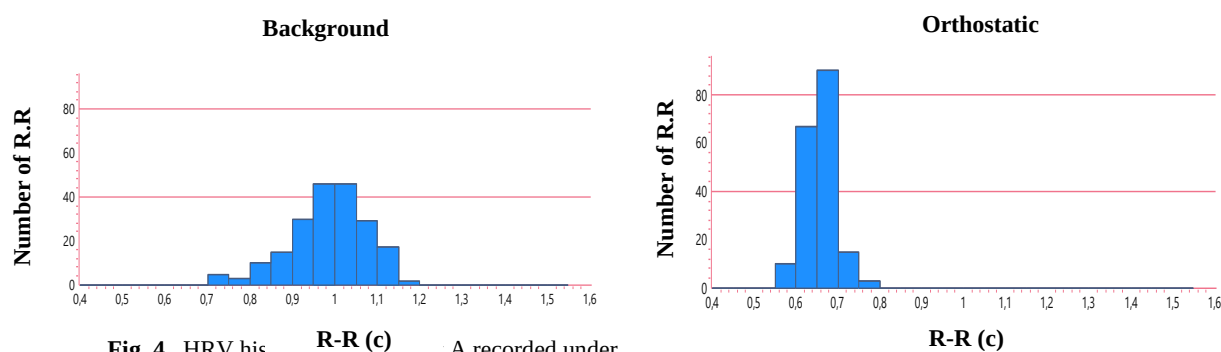


Fig. 4. HRV his R-R (c) A recorded under resting and orthostatic conditions.

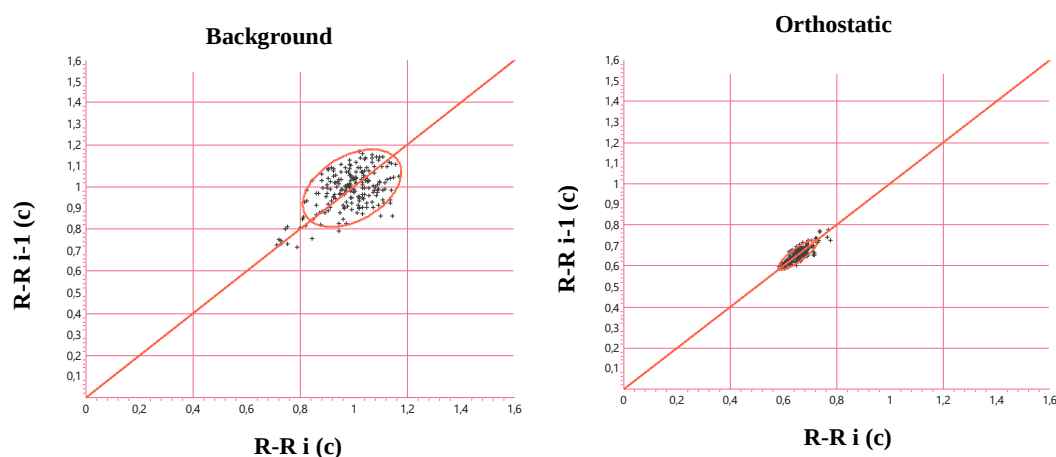


Fig. 5. Poincaré plot (scattergram) of heart rate variability (HRV) of Patient A recorded under resting and orthostatic conditions.

The Poincaré plot demonstrated a broad, symmetrical elliptical pattern, indicating relatively high SD1 and SD2 values and well-preserved short- and long-term heart rate variability (Fig. 5). The large elliptical area reflects adequate autonomic functional reserves and efficient physiological regulation of cardiac activity. Overall, these findings are consistent with preserved autonomic balance and a high cardiovascular adaptive capacity. The autocorrelogram demonstrated a gradual decline in autocorrelation coefficients while maintaining a regular rhythmic pattern, indicating stable autonomic regulatory processes (Fig. 6). These findings suggest coordinated functioning of the central and autonomic mechanisms involved in heart rate control. Preservation of the autocorrelation function reflects a high adaptive capacity of the organism in response to external physiological stressors. According to the Psychotest software protocol for assessing autonomic regulatory mechanisms, the following results were obtained:

Overall autonomic regulatory activity (Total Power, TP): High

Humoral-metabolic/central regulatory activity (Very Low Frequency, VLF): High

Sympathetic nervous system activity (Low Frequency, LF): Moderate

Parasympathetic nervous system activity (High Frequency, HF): High

Characteristics of autonomic regulatory mechanisms

The relative contribution of humoral-metabolic and central regulatory mechanisms was within the physiological reference range.

Autonomic balance: Vagotonia (parasympathetic predominance).

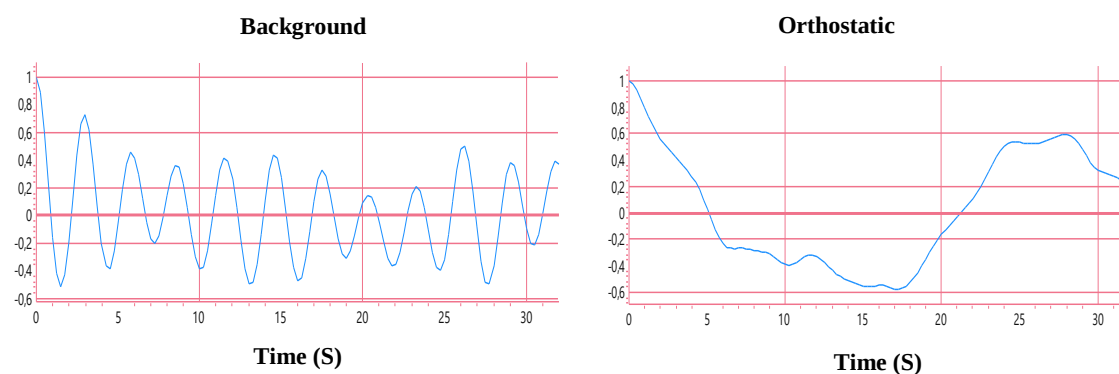


Fig. 6. HRV autocorrelograms of Patient A recorded under resting and orthostatic conditions.

Functional state of autonomic regulation

According to Baevsky's method, the level of regulatory system strain was classified as low, indicating the absence of excessive functional stress on autonomic regulatory mechanisms.

Assessment of autonomic nervous system reactivity

Parasympathetic nervous system reactivity: Moderate

Sympathetic nervous system reactivity: Moderately increased

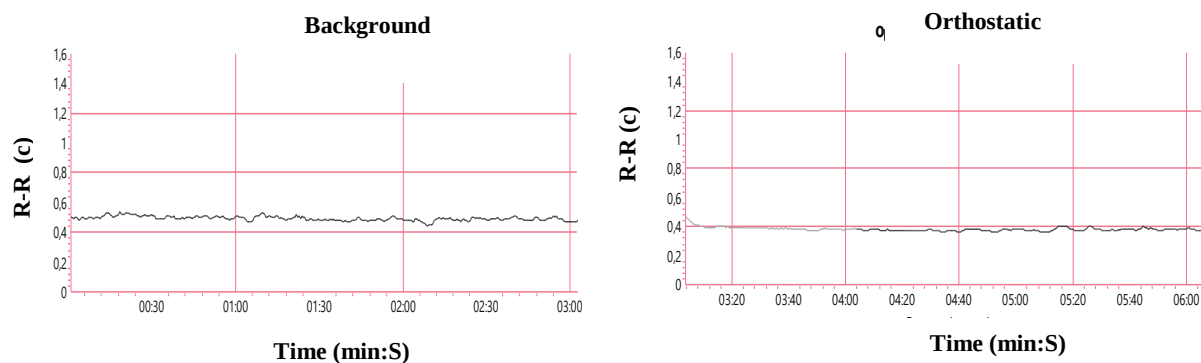


Fig. 7. Heart rate variability (HRV) rhythmograms of Patient B recorded under resting and orthostatic conditions.

Fig. 7 presents the HRV rhythmogram of Patient B. The relatively uniform distribution of R-R intervals indicates reduced heart rate variability and impaired autonomic regulation. This pattern is consistent with increased sympathetic nervous system activity and attenuated vagal modulation. Overall, these findings suggest diminished cardiovascular functional reserves and a reduced adaptive capacity.

The spectrogram showed a reduction in total power (TP) accompanied by a marked decrease in the high-frequency (HF) component, indicating diminished parasympathetic nervous system activity (Fig. 8). The relative predominance of the low-frequency (LF) component, together with an increased LF/HF ratio, suggests a shift in autonomic balance toward sympathetic dominance.

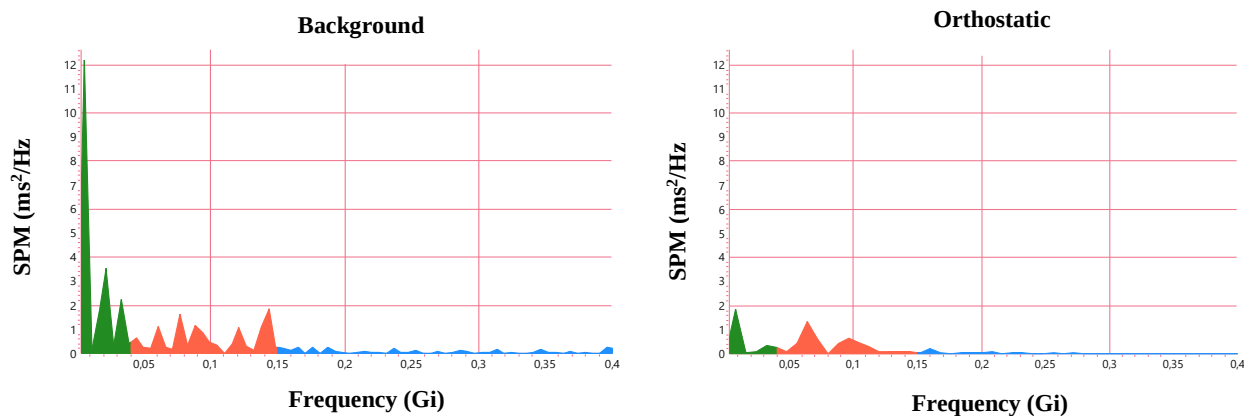


Fig. 8. HRV spectrograms of Patient B recorded under resting and orthostatic conditions.

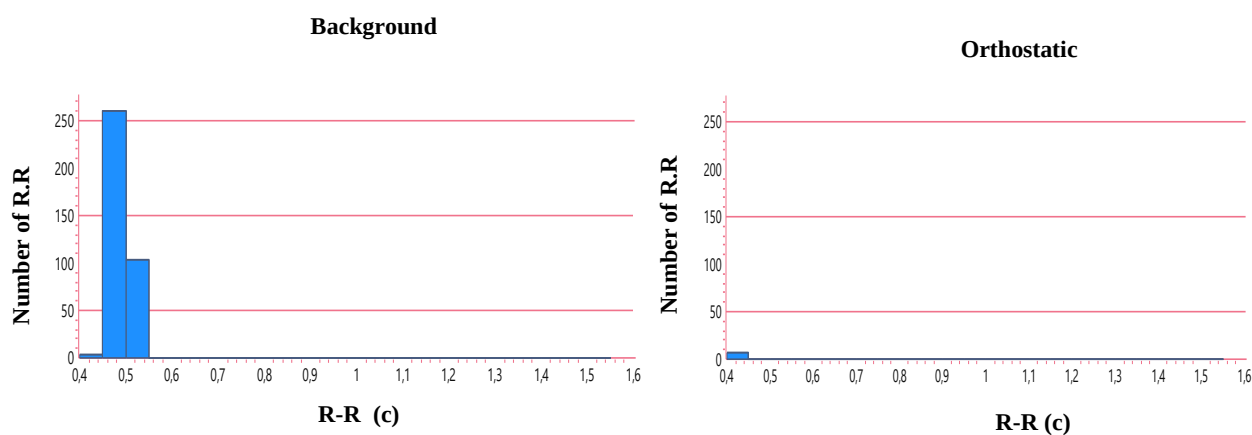


Fig. 9. HRV histograms of Patient B recorded under resting and orthostatic conditions.

The histogram demonstrated a narrowed distribution of the variation series and an increased proportion of the modal interval, indicating reduced heart rate variability (Fig. 9). The elevated stress index (SI) reflects increased functional strain on the autonomic regulatory systems and suggests greater centralization of cardiac rhythm control.

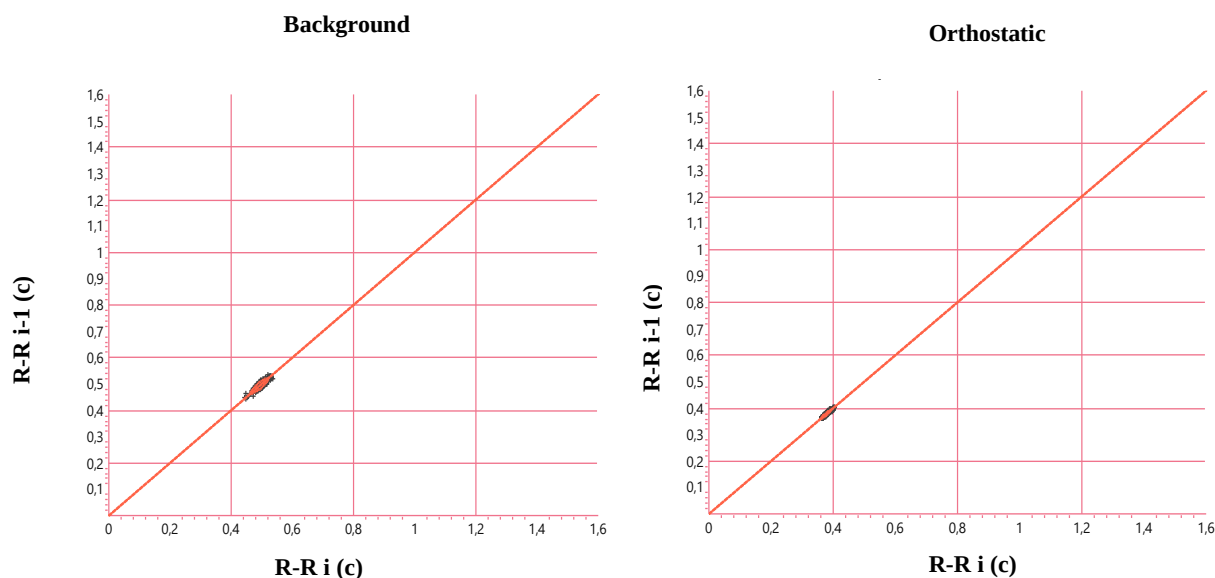


Fig. 10. Poincaré plot (scattergram) of heart rate variability (HRV) of Patient B recorded under resting and orthostatic conditions.

The Poincaré plot demonstrated a markedly reduced elliptical area. The lower SD1 and SD2 values indicate attenuation of short- and long-term heart rate variability, reflecting impaired autonomic modulation (Fig. 10). These findings are consistent with diminished adaptive capacity of the autonomic nervous system and increased sympathetic influence on cardiac regulation. The autocorrelogram showed a rapid decline in autocorrelation coefficients, accompanied by reduced rhythm stability. These findings suggest increased central regulatory influence and decreased efficiency of autonomic regulation (Figure 11). Overall, the results obtained for Patient B indicate greater functional strain on the autonomic regulatory systems and limited adaptive reserves of the organism.

Assessment of autonomic regulatory mechanisms

According to the protocol for assessing autonomic regulatory mechanisms, the following results were obtained:

Overall autonomic regulatory activity (Total Power, TP): Low

Humoral-metabolic/central regulatory activity (Very Low Frequency, VLF): Low

Sympathetic nervous system activity (Low Frequency, LF): Low

Parasympathetic nervous system activity (High Frequency, HF): Low

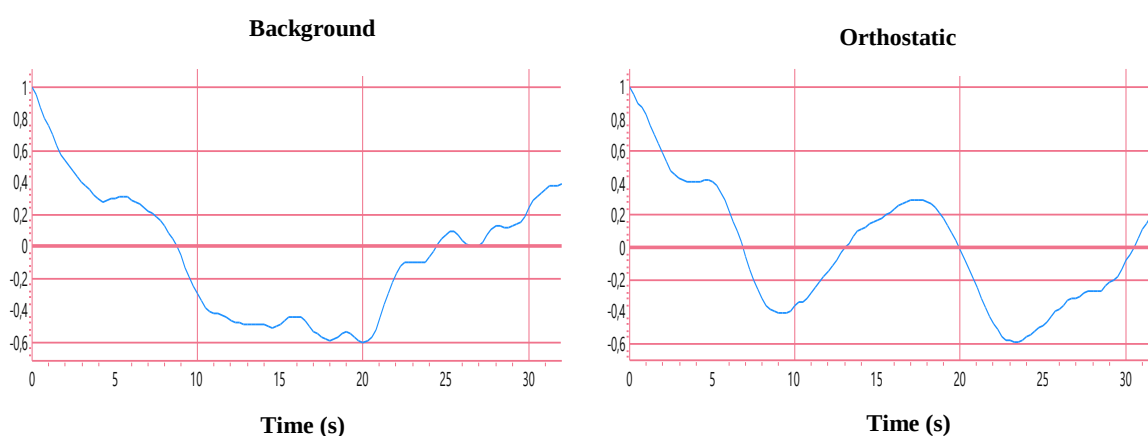


Fig. 11. HRV autocorrelograms of Patient B recorded under resting and orthostatic conditions.

Characteristics of autonomic regulatory mechanisms

The relative contribution of humoral-metabolic and central regulatory mechanisms was increased.

Autonomic balance: Relative sympathicotonia.

Regulatory System Strain (According to Baevsky's Method)

High regulatory system strain.

Assessment of Autonomic Nervous System Reactivity

Parasympathetic nervous system reactivity: Low

Sympathetic nervous system reactivity: Low

DISCUSSION

In the present study, heart rate variability (HRV) parameters were compared between adolescents with regular and irregular sleep schedules. The findings indicate that sleep schedule exerts a significant influence on autonomic nervous system function. Adolescents with a regular sleep schedule demonstrated significantly higher time-domain, frequency-domain, and geometric HRV indices than those with an irregular sleep schedule, suggesting more effective autonomic regulation and better preservation of cardiovascular functional reserves. Among the time-domain indices, SDNN, RMSSD, and pNN50 were significantly higher in adolescents with a regular sleep schedule. SDNN is a key integrative measure of overall heart rate variability and reflects the overall efficiency of autonomic regulation. Reduced SDNN is generally interpreted as evidence of diminished autonomic flexibility, impaired adaptive capacity, and lower functional reserve. Accordingly, the lower SDNN values observed in adolescents with an irregular sleep schedule in the present study may indicate chronic functional strain and a relative predominance of sympathetic nervous system activity. The RMSSD and pNN50 indices are established markers of short-term heart rate variability and are predominantly associated with vagal (n. vagus) modulation.

The significantly higher values observed in adolescents with a regular sleep schedule suggest preserved parasympathetic activity, whereas the lower values in adolescents with an irregular sleep schedule indicate impaired vagal regulation. Collectively, these findings point to a reduced capacity of the cardiovascular system to adapt to both internal and external stressors. The frequency-domain analysis further corroborated these findings. The substantially higher total power (TP) observed in adolescents with a regular sleep schedule reflects more coordinated activity across all levels of autonomic regulation. Reduced TP is considered an important indicator of diminished overall HRV and has been associated with diminished functional reserves of the organism (Sammito *et al.* 2024). Accordingly, the lower TP values observed in adolescents with an irregular sleep schedule indicate impaired adaptive capacity. The higher HF component in the regular sleep schedule group reflects preserved respiratory sinus arrhythmia and active parasympathetic modulation. Lower HF has been linked to chronic stress, sleep deprivation, and increased psycho-emotional stress in previous studies (Li *et al.* 2025). Our findings are consistent with these observations and further suggest that disruption of the sleep schedules leads to impaired vagal control. The LF/HF ratio is widely used as an indicator of the relative contribution of sympathetic and parasympathetic modulation within the autonomic nervous system. The increase in the LF/HF ratio observed during the orthostatic test in both groups represents a normal physiological response, reflecting sympathetic activation in response to postural change. However, in adolescents with an irregular sleep schedule, this increase occurred in parallel with an overall reduction in HRV indices, suggesting reduced adaptive capacity. Although the LF/HF ratio should not be interpreted in isolation, its integration with SDNN, RMSSD, and HF provides a more comprehensive assessment of autonomic regulation. Among the geometric HRV indices, the increase in the stress index (SI) warrants particular attention. According to Baevsky's method, SI reflects the degree of functional strain on autonomic regulatory mechanisms (Brisinda *et al.* 2024). In the present study, adolescents with an irregular sleep schedule exhibited significantly higher SI values, indicating greater sympathetic predominance and enhanced central regulation. The persistence of these differences during orthostatic testing further suggests that their autonomic regulatory systems operate under increased functional strain in response to physiological stress. The findings obtained from the Poincaré plot further corroborated the time-domain and frequency-domain results. Adolescents with a regular sleep schedule demonstrated a larger elliptical area (ell_S), indicating greater HRV and more flexible autonomic regulation. In contrast, the markedly reduced ell_S values observed in adolescents with an irregular sleep schedule reflect reduced heart rate variability and diminished functional reserves. The orthostatic test provided additional evidence regarding the functional capacity of autonomic regulatory mechanisms. In both groups, the increase in heart rate and the reduction in parasympathetic indices represented expected physiological responses to postural change. However, adolescents with a regular sleep schedule maintained relatively higher SDNN, RMSSD, TP, and HF values during the orthostatic stress, suggesting better preservation of cardiovascular functional reserves and more effective adaptation to postural challenge. The findings of the present study are consistent with the international literature. Several studies have shown that sleep deprivation is associated with reduced RMSSD and HF values, increased LF and LF/HF ratios, and a tendency toward lower SDNN values. In addition, poor sleep quality has been reported to impair autonomic regulation, reduce cardiovascular functional reserves, and increase the risk of metabolic disorders (Nevels 2023; Zhang *et al.* 2025). The present results further extend this evidence by indicating that adherence to a regular sleep schedule is an important determinant of normal autonomic function in adolescents. Overall, the results indicate that adherence to a regular sleep schedule is associated with more favorable time-domain, frequency-domain, and geometric HRV indices. In contrast, an irregular sleep schedule is associated with relatively increased sympathetic activity, reduced parasympathetic modulation, and diminished cardiovascular functional reserves. These results underscore the clinical and preventive significance of promoting healthy sleep habits for preserving cardiovascular health during adolescence (Dawson *et al.* 2024; Jaspan *et al.* 2024). In the present study, adolescents with a regular sleep schedule exhibited higher SDNN, RMSSD, pNN50, TP, and HF values, along with lower heart rate (HR) and stress index (SI) values, indicating a predominance of parasympathetic autonomic activity. These findings are consistent with those reported in recent international studies (Zhang *et al.* 2025). Evidence from systematic reviews and meta-analyses indicates that sleep deprivation and poor sleep quality are associated with reductions in SDNN, RMSSD, and HF, as well as increased sympathetic nervous system activity. Such alterations in HRV reflect impaired autonomic cardiovascular regulation and are considered early functional biomarkers of insufficient sleep. Studies in children and adolescents have similarly shown marked changes in HRV across sleep stages. Specifically, RMSSD and HF increase during slow-wave sleep, reflecting enhanced parasympathetic

activity, whereas sympathetic influence becomes more pronounced during rapid eye movement (REM) sleep and immediately before awakening. Accordingly, maintaining a regular sleep schedule is considered an important physiological factor in preserving autonomic balance. In our study, the marked reduction in SDNN observed among adolescents with an irregular sleep schedule indicates decreased overall HRV. As an integral HRV parameter, SDNN reflects the overall efficiency of autonomic regulation, and its reduction suggests diminished autonomic flexibility and impaired adaptive reserves. Recent pediatric studies have further confirmed that SDNN varies with age and may serve as one of the principal indicators for assessing autonomic nervous system function in children and adolescents (Malik *et al.* 2024; Kakavand *et al.* 2025). The RMSSD and pNN50 indices are among the most sensitive markers of short-term vagal activity. In the present study, the lower values observed in adolescents with an irregular sleep schedule indicate impaired parasympathetic modulation. Similar findings have been reported in recent studies of adolescents, in which reductions in RMSSD, pNN50, and HF were associated with increased emotional stress and autonomic dysfunction (Liu *et al.* 2025). The results of the frequency-domain analysis further demonstrated that higher TP and HF values indicate more effective autonomic regulation. Conversely, a reduction in TP reflects an overall decline in heart rate variability and diminished functional reserves of the organism. In the present study, the substantially higher TP values observed in adolescents with a regular sleep schedule indicate better preserved adaptive capacity. Similar findings have been reported in studies investigating the physiology of sleep (Tobaldini *et al.* 2013). The HF component reflects respiratory sinus arrhythmia and vagal activity. The higher HF values observed in adolescents with a regular sleep schedule indicate predominant vagal modulation. In contrast, the reduced HF values in adolescents with an irregular sleep schedule suggest that sleep deprivation adversely affects autonomic nervous system function. Recent studies and meta-analyses have identified HF as one of the HRV parameters most sensitive to changes in sleep quality (Eleonora Tobaldini *et al.* 2013; Suling Zhang *et al.* 2025). The interpretation of the LF/HF ratio has become more cautious in recent years. Although this index was previously regarded as a direct measure of sympathovagal balance, current evidence suggests that it should be interpreted together with SDNN, RMSSD, and HF rather than in isolation. Accordingly, in the present study, the LF/HF ratio was considered as part of a comprehensive assessment of HRV rather than as an independent indicator. During the orthostatic test, both groups showed an increase in the LF/HF ratio accompanied by a decrease in HF, reflecting a normal physiological sympathetic response to postural change. However, adolescents with a regular sleep schedule maintained relatively high SDNN, RMSSD, and TP values, indicating adequate functional reserves and effective autonomic adaptation. Similar patterns of cardiovascular adaptation to postural change have been described in large-scale studies involving children and adolescents (Bardia Kakavand *et al.* 2025).

CONCLUSION

Overall, our findings are consistent with current international evidence and further show that maintaining a regular sleep schedule plays a crucial role in preserving heart rate variability, supporting parasympathetic autonomic activity, and maintaining the adaptive reserves of the cardiovascular system in adolescents. These findings underscore the clinical and preventive importance of sleep hygiene interventions aimed at promoting healthy sleep habits during adolescence.

Conflicts of interest

The authors declare that there is no conflict of interest.

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