

HEART RATE VARIABILITY AND SLEEP: A WINDOW INTO AUTONOMIC REGULATION IN HEALTH AND DISEASE

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ABSTRACT

Sleep is not merely a passive resting state but a complex physiological process marked by dynamic shifts in autonomic nervous system (ANS) activity. Heart rate variability (HRV), a non-invasive measure of autonomic modulation, reflects these changes across different sleep stages. This review discusses the physiological and pathological aspects of HRV during sleep, drawing on insights from recent studies, particularly the comprehensive review by Tobaldini et al. (2013). The paper emphasizes linear and non-linear HRV analysis techniques and explores the autonomic implications in disorders such as obstructive sleep apnea (OSA), insomnia, and restless leg syndrome (RLS).

KEYWORDS: Heart Rate Variability, Sleep, Autonomic Nervous System, Obstructive Sleep Apnea, Insomnia, Non-linear Analysis, Entropy, SUDEP.

1. INTRODUCTION

Heart rate variability (HRV) refers to the variation in the time interval between successive heartbeats, reflecting autonomic nervous system (ANS) regulation. Since HRV is sensitive to internal and external stimuli, it serves as a valuable biomarker of physiological and psychological states.^[1] The modulation of sympathetic and parasympathetic tones governs vital functions such as heart rate and blood pressure. Heart rate variability (HRV) offers a dynamic, non-invasive method to assess these autonomic functions. Sleep is a critical period for autonomic regulation and restoration, and HRV patterns during sleep offer a unique lens through which to assess sleep quality, stress, and health risks.^[2] Sleep disturbances are increasingly associated with elevated cardiovascular risks, making HRV an essential tool in both research and clinical practice.

2. PHYSIOLOGICAL BASIS OF HRV AND SLEEP

2.1 Physiology of HRV and Measurement Techniques

The ANS regulates heart function through two branches: the sympathetic nervous system (SNS), which is responsible for the "fight or flight" response, and the parasympathetic nervous system (PNS), which promotes "rest and digest" functions. HRV is influenced by the balance between these two branches, with higher HRV indicating a dominant parasympathetic influence and lower HRV suggesting sympathetic dominance or

autonomic dysregulation.

HRV is commonly assessed using time-domain, frequency-domain, and non-linear measures. HRV can be derived from ECG (gold standard), PPG (photoplethysmography), or wearable sensors, though accuracy varies. Time-domain indices include SDNN (standard deviation of NN intervals) and RMSSD (root mean square of successive differences), while frequency-domain measures such as LF (low frequency) and HF (high frequency) bands correspond to sympathetic and parasympathetic activity, respectively.^[3] Non-linear measures include Poincaré plots, entropy measures.

HRV reflects the interplay between sympathetic and parasympathetic branches of the ANS. High-frequency (HF) components (0.15–0.4 Hz) are associated with parasympathetic activity, while low-frequency (LF) components (0.04–0.15 Hz) reflect a mix of sympathetic and parasympathetic influences. The LF/HF ratio is commonly interpreted as a marker of sympathovagal balance.^[4]

Modern wearable devices and photoplethysmography (PPG)-based sensors have enabled long-term and non-invasive HRV monitoring, making sleep-related HRV studies more accessible outside clinical settings.^{[5],[6]}

2.2. The Sleep Cycle and Its Stages

Sleep is divided into two major categories: **Non-Rapid Eye Movement (NREM)** sleep and **Rapid Eye Movement (REM)** sleep. NREM sleep is further subdivided into three stages: N1, N2, and N3. Each stage is characterized by different patterns of brain activity, muscle tone, and autonomic regulation, which in turn influence HRV.

- **N1 (Light sleep):** A transitional stage where HRV increases slightly due to parasympathetic activation.
- **N2 (Stable sleep):** The body enters a more stable state of rest, with moderate increases in parasympathetic activity and HRV.
- **N3 (Deep sleep):** Also known as slow-wave sleep, this stage is characterized by a pronounced parasympathetic dominance, leading to the highest HRV levels.
- **REM (Rapid Eye Movement):** While brain activity is high during REM sleep, HRV tends to be lower due to sympathetic activity and muscle atonia.^[7]

3. HRV ACROSS SLEEP STAGES

Sleep is broadly divided into non-REM (NREM) and rapid eye movement (REM) stages, each showing distinct HRV patterns. NREM sleep, particularly stages N2 and N3, is marked by parasympathetic dominance, characterized by high HF and low LF components. In contrast, REM sleep exhibits sympathetic predominance, with reduced HRV and increased cardiovascular variability.

The transition from wake to sleep is associated with a shift from sympathetic to parasympathetic modulation. These patterns are further modulated by the cyclic nature of sleep stages, circadian rhythm, and arousal-related EEG fluctuations such as cyclic alternating patterns (CAP).

3.1. NREM Sleep (Non-Rapid Eye Movement)

This includes stages N1, N2, and N3 (slow-wave sleep).

- **General ANS Pattern:** Dominated by **parasympathetic** (vagal) activity.
- **HRV Characteristics:**
 - **High HF (High-Frequency) power:** Reflects strong vagal tone.
 - **Low LF (Low-Frequency) power** and **LF/HF ratio:** Indicates reduced sympathetic influence.
 - **Lower heart rate** compared to wakefulness and REM.
- **Stage N3 (deep sleep)** shows **maximum parasympathetic dominance**, often with the highest RMSSD and HF power values.

3.2. REM Sleep (Rapid Eye Movement)

- **General ANS Pattern:** Marked by **autonomic instability** with increased **sympathetic activity**.
- **HRV Characteristics:**
 - **Higher LF power** and **LF/HF ratio:** Indicating a shift toward sympathetic dominance.
 - **Reduced HF power** compared to NREM.
 - **Heart rate increases**, and its variability becomes more irregular.
 - May exhibit brief bursts of sympathetic surges, particularly associated with vivid dreams or arousals.

3.3. Wakefulness (before sleep onset and during nocturnal awakenings)

- **Mixed sympathetic and parasympathetic activity**, depending on relaxation level.
- **HRV is variable**, but generally shows **lower parasympathetic tone** than NREM.

Table 1: HRV Characteristics Across Sleep Stages.

Sleep Stage	HF Power (Parasympathetic)	LF Power (Sympathetic + Parasympathetic)	LF/HF Ratio	Heart Rate
Wakefulness	Moderate	Moderate	~1	High
NREM (N1/N2)	High	Low	<1	Decreasing
Slow Wave Sleep (N3)	Very High	Very Low	<<1	Lowest
REM Sleep	Low	High	>1	Variable

4. FACTORS AFFECTING HRV DURING SLEEP

Several factors can modulate HRV during sleep, including:

- **Age:** HRV tends to decrease with age, reflecting a decline in autonomic regulation.
- **Physical Fitness:** Higher levels of physical fitness are associated with higher HRV, reflecting better autonomic regulation.
- **Stress:** Chronic stress and mental health conditions, such as anxiety and depression, can reduce HRV and impair sleep quality.

- **Medications:** Certain medications, such as beta-blockers, can increase HRV, while others, like stimulants, may decrease it.

4.1 Sleep Architecture and HRV

Research shows that the amount and distribution of time spent in different sleep stages significantly impacts HRV. For example, people with high-quality sleep tend to spend more time in deep N3 sleep, which correlates with higher HRV. Conversely, individuals with disrupted sleep, such as those with insomnia or sleep apnea, may experience fragmented sleep cycles with less time spent in deep sleep, leading to lower HRV.

Studies have also observed that the presence of sleep disturbances, such as frequent awakenings or reduced time spent in restorative sleep stages, is associated with a decrease in overall HRV. These findings emphasize the importance of sleep quality—not just sleep duration—in determining autonomic regulation and health outcomes.

5. HRV ANALYSIS: LINEAR AND NON-LINEAR METHODS

Linear HRV analysis, using time and frequency domain parameters, remains widely used. LF and HF bands serve as proxies for sympathetic and parasympathetic tones, though the interpretation of LF remains debated.

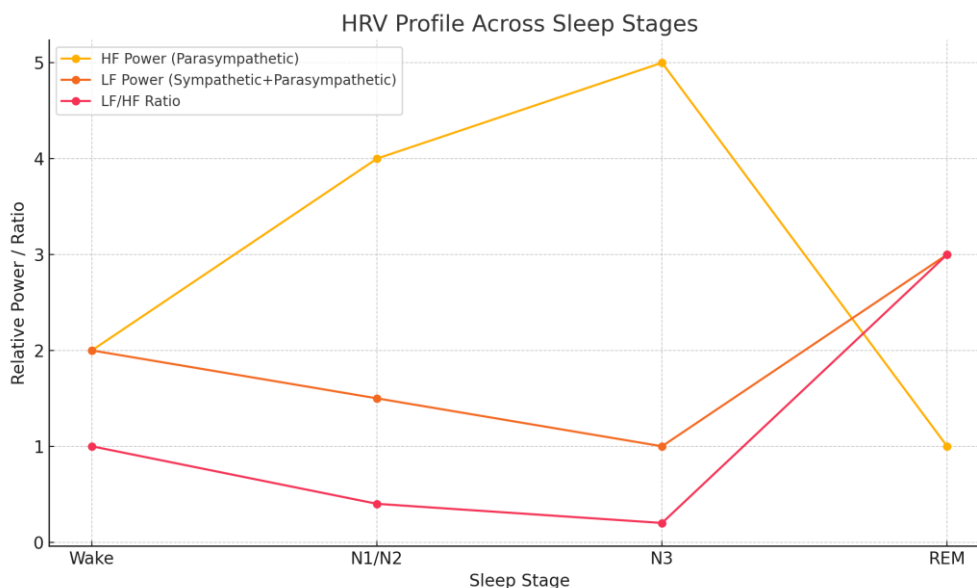


Figure 1. HRV Metrics Across Sleep Stages.

Non-linear methods, including entropy-based metrics such as Shannon entropy and corrected conditional entropy (CCE), evaluate the complexity of HR dynamics. Reduced entropy in REM sleep and in aging populations suggests decreased adaptive capability and heightened stress vulnerability.^[8]

6. HRV IN SLEEP DISORDERS

6.1 Sleep Disordered Breathing (SDB)

OSA, the most prevalent form of SDB, is associated with intermittent hypoxia, arousals, and increased sympathetic activation. HRV patterns show elevated LF/HF ratios and reduced total variability. CPAP therapy has shown efficacy in normalizing HRV patterns and improving cardiovascular outcomes.^[9]

6.2 Insomnia

Primary insomnia is associated with increased sympathetic activity and reduced vagal tone, leading to lower HF and higher LF components during sleep.^[10] Entropy analyses reveal reduced HRV complexity, suggesting impaired cardiovascular regulation.^[11]

6.3 RLS and Periodic Limb Movement Disorder

Associated with transient sympathetic surges and HRV disruptions during arousals.^[12]

7. CLINICAL AND RESEARCH IMPLICATIONS

HRV analysis serves as a potent diagnostic and prognostic tool for sleep-related disorders.

- **Sleep quality monitoring:** HRV features can help classify sleep stages and evaluate sleep architecture.
- **Stress and mental health evaluation:** Nighttime HRV correlates with stress resilience and emotional regulation.
- **Cardiovascular risk stratification:** Reduced HRV during sleep is associated with increased mortality in cardiac patients.^[13]

Advances in wearable technology, cloud computing, and AI now facilitate large-scale HRV data analysis and individualized sleep profiling.^[14]

8. CONCLUSION

The relationship between HRV and sleep stages provides a detailed view of how the autonomic nervous system regulates various physiological processes during sleep. High HRV during NREM sleep, particularly in deep sleep (N3), reflects optimal autonomic functioning and is associated with better health outcomes. Conversely, reduced HRV in REM sleep and other sleep disruptions may signal underlying health issues, including sleep disorders, cardiovascular diseases, and mental health concerns.

Understanding HRV in the context of sleep stages offers valuable insights into sleep quality and the autonomic regulation that supports recovery and well-being. Monitoring HRV across sleep stages may thus serve as an effective strategy for assessing sleep health and detecting early signs of sleep-related disorders.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

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