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Heart Rate Variability (HRV) as an Objective Indicator of the Stress Response: Physiological Mechanisms, Diagnostic Potential, and Clinical Applications

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Abstract

Heart rate variability (HRV) has gained recognition as a biomarker of autonomic nervous system activity and the body's adaptive capacity. This review discusses the physiological foundations of HRV and its relationship to the body's response to both acute and chronic stress. The main methods of HRV measurement are: time-domain, frequency-domain, and nonlinear. These are presented, along with their advantages, limitations, and key technical requirements. Particular attention is given to the application of HRV in the diagnosis, treatment, and prevention of stress-related disorders such as depression and anxiety, as well as the potential use of HRV biofeedback and mobile monitoring technologies. The review highlights current limitations in interpretative standards, the influence of confounding factors, and the need for individualized analysis. The potential for artificial intelligence tools to personalize stress assessment is also discussed. Despite growing clinical interest, HRV requires further standardization and research to enhance its utility
as a tool for assessing psychophysiological states.

Keywords: heart rate variability, HRV, stress, autonomic nervous system, biofeedback, mental health

1. Introduction

Stress is a ubiquitous and inherent aspect of human life. However, its chronic presence is associated with numerous adverse health outcomes, both somatic and psychological. The body's stress response involves a series of complex physiological processes, primarily driven by the activation of the hypothalamic–pituitary–adrenal (HPA) axis and the autonomic nervous system (ANS), leading to significant changes in the function of various organ systems [1].

In this context, heart rate variability (HRV), the physiological fluctuation of intervals between consecutive heartbeats, has garnered increasing scientific interest. HRV reflects the dynamic balance between sympathetic and parasympathetic activity of the ANS and is considered a non-invasive biomarker of emotional regulation and the body's adaptive capacity [2,3].

In recent years, HRV has attracted attention as a potential indicator of stress levels in both experimental and clinical settings. Research has shown that low HRV is associated with heightened stress reactivity, reduced psychological resilience, and increased risk of anxiety, depressive and psychosomatic disorders [4–6].

The advancement of mobile technologies and physiological monitoring methods has facilitated the widespread use of HRV in everyday settings, further enhancing its potential in health diagnostics and prevention. Despite the growing volume of publications, HRV interpretation in the context of stress remains fraught with challenges. Measurement standards and clinical applications are still under investigation [7].

The aim of this review is to provide an up-to-date overview of the relationship between HRV and the human stress response. It discusses the physiological mechanisms underlying HRV, methods of measurement, stress-related changes, and potential clinical and therapeutic applications. The paper also highlights current limitations and proposes directions for future research in the field.

2. Physiological Basis of HRV and the Stress Response

Heart rate variability reflects complex interactions between the parasympathetic and sympathetic branches of the autonomic nervous system (ANS). At rest, vagal activity predominates, resulting in high HRV and promoting physiological balance, as well as effective regulation of cognitive and emotional processes [2,8].

Under conditions of psychological or physiological stress, sympathetic activity increases through activation of the sympatho-adrenal axis. This is accompanied by an elevated heart rate, metabolic mobilization, and a reduction in HRV, interpreted as an adaptive "fight-or-flight" response [4]. In a meta-analysis of individuals exposed to stress, Kim et al. (2018) demonstrated a significant reduction in HRV, reflecting a shift in autonomic balance toward sympathetic dominance and diminished parasympathetic influence [4].

The physiological basis of HRV has also been extensively described in the neurovisceral integration model proposed by Thayer and Lane. This model posits a functional feedback loop connecting cortical structures (especially the prefrontal cortex), the limbic system (including the amygdala), the brainstem, and the heart. This interconnected neural network enables coordinated regulation of both cognitive and autonomic functions. In this context, HRV is not merely a parameter reflecting cardiac activity, but a marker of the body's overall capacity for flexible adaptation and emotional regulation [9].

Thus, HRV serves as a sensitive neurophysiological indicator that allows for non-invasive assessment of autonomic balance and may function as a biomarker of emotional regulation capacity and adaptability in response to stress.

3. Methods of Heart Rate Variability (HRV) Measurement and Analysis

3.1. Time-Domain Methods

Time-domain analysis of heart rate variability is based on evaluating fluctuations in RR intervals over time. Commonly used indices include SDNN (standard deviation of normal-to-normal intervals), which represents overall HRV and integrates both sympathetic and parasympathetic influences. RMSSD (root mean square of successive differences) reflects short-term variability and serves as an indirect indicator of vagal activity. Another useful parameter is pNN50- the percentage of successive RR intervals differing by more than 50 mswhich also reflects parasympathetic modulation. These methods are particularly useful for short-term HRV assessments and are often employed in studies of psychophysiological stress, emotional functioning, and homeostatic regulation [2,7].

3.2. Frequency-Domain Methods

Frequency-domain methods, also known as spectral analysis of HRV, assess the influence of the autonomic nervous system based on the distribution of power across specific frequency bands within the RR signal. The signal is transformed from the time to the frequency domain, typically using Fast Fourier Transform (FFT) or autoregressive (AR) modeling, which require recordings of at least 2–5 minutes [10]. Spectral analysis distinguishes three main components: HF (High Frequency, 0.15–0.4 Hz)- primarily associated with respiration and parasympathetic activity, LF (Low Frequency, 0.04–0.15 Hz)- historically interpreted as a marker of mixed sympathetic and parasympathetic activity, LF/HF ratio. LF/HF ratio was once considered a measure of sympathovagal balance. However, this interpretation has faced criticism due to the influence of breathing patterns, emotions, body posture, and physical activity on HRV components [11,12].

3.3. Nonlinear Methods

Nonlinear HRV analysis captures the complexity of heart rhythm dynamics, which linear methods may fail to represent. Common techniques include Poincaré plots, from which SD1 (reflecting short-term variability) and SD2 (reflecting long-term variability) indices are derived. Entropy-based measures such as Approximate Entropy (ApEn) and Sample Entropy (SampEn) evaluate the unpredictability of the signal- lower values indicate reduced complexity and may suggest impaired autonomic adaptability. Another valuable method is Detrended Fluctuation Analysis (DFA), which analyzes the fractal structure of the signal and long-range correlations. Although nonlinear methods require more advanced data processing, they provide additional insight into autonomic function, especially in the context of aging, chronic diseases or psychophysiological disorders [13–15].

3.4. Technical Requirements and Measurement Conditions

Accurate HRV analysis requires adherence to specific technical and environmental standards to ensure the reliability and reproducibility of results. The RR signal, necessary for calculating HRV parameters, can be recorded using traditional electrocardiography (ECG)- considered the gold standard or via photoplethysmography (PPG), increasingly used in mobile devices such as wristbands, smartwatches or rings that monitor vital signs [2,7].

HRV measurement should be conducted in a controlled environment- seated or supine position, following at least five minutes of rest, in a room with stable temperature and minimal external stimuli such as noise, light or thermal fluctuations [7,10]. To minimize confounding effects, it is also recommended to avoid physical activity, caffeine, nicotine or emotionally stimulating situations prior to measurement.

The quality of the RR signal is crucial for valid HRV analysis. Even minor artifacts or errors in detecting R-peaks can significantly distort HRV values, especially in short-term or frequency-domain assessments. Therefore, signal preprocessing is essential, including identification and removal of abnormal intervals. Additionally, removed segments should be reconstructed using standardized interpolation methods to preserve the temporal structure of the signal. Failure to correct artifacts may lead to reduced data reliability and misleading diagnostic or research conclusions [16].

4. HRV as an Indicator of the Physiological Stress Response

Both acute and chronic stress affect heart rate variability components, particularly those related to parasympathetic activity. A reduction in HRV indicates a dominance of the sympathetic nervous system, which is characteristic of the physiological mobilization response to stress [3,6].

4.1. HRV in Response to Acute Stress

Acute stress is associated with the immediate activation of the hypothalamic–pituitary–adrenal axis and the sympathetic nervous system. This is accompanied by a characteristic increase in heart rate and a decrease in HRV parameters, especially in the high-frequency component and RMSSD- both markers of parasympathetic activity [4].

In experimental settings, such as the Trier Social Stress Test (TSST), significant reductions in HRV, particularly in parasympathetic components, are observed during exposure to the stressor, followed by a partial recovery during the post-stress phase. In a study by Spellenberg et al. (2020), the TSST was administered to 24 healthy participants, and a significant reduction in mean RR intervals and SDNN was noted during the stress phase, with a partial return of these values during recovery. The authors concluded that baseline HRV levels, as measured by SDNN and RMSSD, influence the speed of return to homeostasis- reflecting greater autonomic flexibility and psychophysiological resilience [17].

4.2. HRV and Chronic Stress

In the context of prolonged stress exposure, research indicates a persistent reduction in parasympathetic activity and overall heart rate variability (HRV). Schubert et al. (2009) observed that individuals experiencing chronic stress exhibited significantly reduced heart rate complexity, as reflected by lower values of the nonlinear HRV parameter D2. This diminished complexity suggests impaired autonomic adaptability and reduced physiological flexibility, potentially limiting the system's ability to modulate heart rate in response to blood pressure fluctuations [18].

Studies have shown that low HRV is characteristic of individuals suffering from depression and anxiety disorders [19,20]. The underlying mechanisms include dysregulation of the HPA axis, chronic sympathetic overactivation and elevated levels of pro-inflammatory cytokines, which may contribute to metabolic and cardiovascular dysfunction [21].

4.3. HRV as a Biomarker of Stress

Due to its sensitivity, HRV is often used as an objective marker of stress load- both in scientific research and in clinical practice. Low HRV may indicate persistent stress activation, while an increase in HRV following interventions (e.g., relaxation techniques, biofeedback therapy, or psychotherapeutic approaches) may suggest improvement in psychophysiological state [5].

However, the interpretation of HRV as a stress biomarker requires consideration of confounding factors such as age, lifestyle, circadian rhythms, medication use, and comorbid health conditions [22].

5. Applications of HRV in the Diagnosis, Therapy, and Prevention of Stress-Related Disorders

In recent years, heart rate variability has gained significant relevance as a non-invasive tool supporting the diagnosis and monitoring of treatment for mental disorders related to stress [2].

5.1. HRV as a Diagnostic Aid in Mental Health Disorders

Individuals suffering from depression, generalized anxiety disorder (GAD), or social phobia often exhibit significantly reduced resting HRV [6,20,23]. A meta-analysis by Kemp et al. (2010) clearly confirmed a substantial reduction in HRV parameters in patients with depression compared to healthy controls [20]. A low HRV value may signal a risk of relapse or insufficient efficacy of pharmacological treatment [19].

5.2. HRV in Therapy and Monitoring of Treatment Progress

Resonance frequency HRV biofeedback is based on synchronizing breathing with the cardiac cycle. This practice can increase HF-HRV, reduce emotional tension, and enhance the body's adaptive capacity [24,25]. Additionally, Goessl and colleagues (2017), in a meta-analysis, demonstrated that HRV biofeedback effectively reduces stress and anxiety in both healthy individuals and clinical populations [26]. HRV is also proving to be a useful indicator of the effectiveness of cognitive-behavioral therapy, as shown in studies reporting increased HRV after treatment- suggesting improved autonomic regulation and potentially reduced cardiovascular risk [27].

5.3. HRV in Stress Prevention and Chronic Disease Risk Reduction

HRV monitoring is useful in preventive programs for individuals exposed to chronic occupational stress (e.g., healthcare workers), helping to identify overload and initiate preventive actions before the onset of burnout or mental health disorders [40]. Among trauma-exposed populations (e.g., military veterans), low baseline HRV may predispose individuals to emotional dysregulation following extreme experiences [29].

5.4. Technologies Supporting HRV Measurement and Analysis

Thanks to mobile devices (smartwatches, wristbands, apps such as HRV4Training and Elite HRV), short-term HRV measurements can now be taken in everyday conditions, enabling remote and continuous monitoring of users' psychophysiological state [30]. Many of these tools integrate self-regulation features such as respiratory biofeedback or meditation, although large-scale studies and standardization of app-supported interventions are still lacking [31].

5.5. Limitations and Clinical Challenges

The use of HRV in clinical practice and preventive interventions involves several important limitations. Firstly, there is still a lack of consistent and widely accepted interpretative norms, which complicates the clinical assessment of HRV results [32]. Secondly, HRV measurements are highly sensitive to confounding factors such as alcohol consumption, acute stress, sleep quality, physical activity, medications, and circadian rhythms, all of which may reduce the reliability of HRV in evaluating psychophysiological status [22]. Additionally, short-term HRV recordings, commonly used in mobile applications, are not always comparable with results obtained from continuous 24-hour Holter monitoring. Discrepancies also exist between various HRV analysis methods, and the lack of standardization in analytical algorithms hinders the comparability of study results and limits the utility of HRV as a standardized tool in clinical practice [32].

6. Individualization of HRV Analysis: Challenges and Future Perspectives

Sinus heart rate variability (HRV) has gained recognition as an objective indicator of psychophysiological status; however, its interpretation still faces significant limitations due to the lack of reference to individual norms. In both clinical and research contexts, there is a growing emphasis on the need to analyze HRV values relative to a person’s own baseline level, rather than exclusively against population norms, which are characterized by high interindividual variability [22].

HRV is strongly modulated by constitutional factors such as age, sex, temperament, level of physical activity and personality traits, as well as by situational context- such as time of day, presence of a stressor, or current emotional state [22,33]. Studies have shown that individuals with different stress coping strategies may exhibit distinct patterns of autonomic activity despite having similar resting HRV values [34].

This has led to a growing call for personalized approaches to HRV interpretation, taking into account a patient's medical history, psychological profile and current psychosocial conditions. It may also be necessary to incorporate subjective contextual data (e.g., perceived stress, mood, sleep quality), rather than relying solely on recorded physiological signals [22].

Increasing optimism surrounds the use of artificial intelligence (AI) and machine learning tools that could integrate HRV measurements with contextual data to develop predictive models tailored to the individual. Such approaches may eventually allow for the development of more sensitive and accurate stress indicators and facilitate better matching of interventions (e.g., biofeedback or therapy) to user needs [35].

For this reason, future HRV research should aim not only to improve measurement accuracy but also to develop theoretical frameworks and analytical methods that enable an individualized, rather than merely population-based, approach to interpreting this parameter.

7. Summary and Conclusions

Heart rate variability (HRV) represents a valuable biomarker of autonomic nervous system activity and the body's capacity to adapt to stress. Low HRV is associated with reduced psychological resilience and an increased risk of emotional disorders. Although HRV analysis methods are becoming increasingly accessible, especially due to advancements in mobile technology, their interpretation still faces significant challenges related to the influence of external factors, the absence of standardized population norms, and high individual variability.

The use of HRV in the diagnosis, treatment, and prevention of stress-related conditions holds promising potential, but it requires further standardization and a more nuanced consideration of the patient's psychological context. In the future, the development of artificial intelligence-based methods may enable more personalized and accurate assessments of psychophysiological status, thereby supporting more effective therapeutic interventions.

Disclosure

Author's Contribution

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