A Comprehensive Study of Heart Rate Variability in Autonomic Nervous System Assessment

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ABSTRACT

Heart rate variability (HRV) provides a non-invasive window into autonomic nervous system function. This study examined the relationship between time-domain and frequency-domain HRV metrics across different physiological states. We recruited 150 healthy participants aged 25-55 years and measured HRV during rest, mental stress, and physical exercise. Results showed significant correlations between RMSSD and high-frequency power ($r=0.78$, $p<0.001$), confirming parasympathetic origins. The LF/HF ratio increased during mental stress ($p<0.01$) but showed high inter-individual variability. These findings support the use of HRV as a biomarker for autonomic assessment while highlighting the need for standardized protocols.

Keywords: heart rate variability, autonomic nervous system, parasympathetic, sympathetic, time-domain analysis, frequency-domain analysis

1. Introduction

The autonomic nervous system (ANS) regulates involuntary physiological processes including heart rate, blood pressure, and digestion. Heart rate variability (HRV), the variation in time intervals between consecutive heartbeats, has emerged as a key indicator of ANS function. Since the landmark study by Akselrod et al. (1981), HRV analysis has been applied across cardiology, psychology, and sports science.

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2. Background

2.1 Autonomic Nervous System

The sympathetic and parasympathetic branches of the ANS exert opposing effects on the sinoatrial node. Sympathetic activation increases heart rate through norepinephrine release, while parasympathetic (vagal) activation decreases heart rate via acetylcholine. This dual innervation allows rapid adjustment to physiological demands.

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2.2 HRV Metrics

Time-domain metrics include SDNN (standard deviation of NN intervals), RMSSD (root mean square of successive differences), and pNN50 (percentage of successive intervals differing by more than 50ms). Frequency-domain analysis using Fast Fourier Transform reveals power in very low frequency (VLF, 0.003-0.04 Hz), low frequency (LF, 0.04-0.15 Hz), and high frequency (HF, 0.15-0.4 Hz) bands.

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3. Materials and Methods

3.1 Participants

One hundred and fifty healthy volunteers (75 male, 75 female) were recruited from the local community. Inclusion criteria: age 25-55 years, no cardiovascular disease, no medications affecting heart rate. Exclusion criteria: diabetes, hypertension, BMI > 30 kg/m². The study was approved by the University Ethics Committee (Protocol #2023-001).

3.2 ECG Recording

A three-lead ECG was recorded using Ag/AgCl electrodes (3M Red Dot 2560) at a sampling rate of 1000 Hz. Recordings were made using a Biopac MP160 data acquisition system with AcqKnowledge software (version 5.0). Electrode placement followed standard Lead II configuration.

3.3 Protocol

Each participant completed three conditions: (1) 10-minute supine rest, (2) 5-minute mental arithmetic task (serial sevens), and (3) 5-minute moderate cycling at 60% predicted maximum heart rate. A 5-minute recovery period separated each condition.

3.4 Data Analysis

R-peaks were detected using the Pan-Tompkins algorithm implemented in Python. Artefacts were removed using adaptive filtering with a threshold of 20% deviation from local mean. HRV metrics were computed using the hrv-analysis package (version 2.0). Statistical analysis was performed in R (version 4.2) using repeated-measures ANOVA with Bonferroni correction.

4. Results

4.1 Participant Characteristics

Table 1: Participant characteristics (N=150)

Characteristic	Mean ± SD	Range
Age (years)	38.2 ± 8.7	25-55
BMI (kg/m²)	24.1 ± 3.2	18.5-29.8
Resting HR (bpm)	68.4 ± 10.2	48-92
SDNN (ms)	142.3 ± 45.6	62-285
RMSSD (ms)	38.7 ± 18.4	12-98

4.2 HRV Changes Across Conditions

Significant differences in HRV metrics were observed across the three conditions ($F(2,298)=45.7$, $p<0.001$, partial $\eta^2=0.23$). Post-hoc comparisons revealed that RMSSD decreased significantly from rest (38.7±18.4 ms) to mental stress (28.3±14.2 ms, $p<0.001$) and exercise (18.9±8.7 ms, $p<0.001$). The LF/HF ratio increased from 1.82±0.94 at rest to 3.45±1.67 during mental stress ($p<0.01$).

Table 2: HRV metrics across conditions (mean±SD)

Metric	Rest	Mental Stress	Exercise	p-value
SDNN (ms)	142.3±45.6	98.4±32.1	65.2±21.8	<0.001
RMSSD (ms)	38.7±18.4	28.3±14.2	18.9±8.7	<0.001
LF (ms²)	1245±567	1678±734	892±312	<0.01
HF (ms²)	684±298	486±234	187±89	<0.001
LF/HF	1.82±0.94	3.45±1.67	4.77±2.34	<0.001

5. Discussion

Our findings confirm that HRV metrics reflect autonomic modulation during different physiological states. The strong correlation between RMSSD and HF power supports the interpretation of these metrics as parasympathetic indices. However, the high variability in LF/HF ratio during mental stress suggests caution when using this metric as a marker of sympathovagal balance. Individual differences in stress reactivity may account for the observed variance.

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6. Conclusions

This study demonstrates that HRV provides a reliable non-invasive assessment of autonomic function across different physiological states. Time-domain metrics, particularly RMSSD, show consistent patterns that reflect vagal tone. Frequency-domain analysis offers additional insights but requires careful interpretation, especially for the LF band and LF/HF ratio. Future research should focus on establishing normative values and standardizing measurement protocols to enhance clinical utility.

The findings have implications for clinical practice in cardiology, stress management, and sports medicine. HRV biofeedback interventions may benefit from targeting specific metrics based on individual baseline characteristics.

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Appendix A: Supplementary Data

This appendix contains additional statistical analyses and raw data summaries that support the main findings presented in the Results section.

A.1 Subgroup Analysis

When stratified by age group (25-39 vs 40-55 years), younger participants showed higher baseline RMSSD (42.3±19.8 vs 35.1±16.2 ms, $p<0.05$) but similar stress-induced changes.