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CLINICAL REVIEW

Heart Rate Variability – Methods and Analysis in Sports Medicine and Exercise Science

Herzratenvariabilität – Methoden und Analyse in Sportmedizin und Trainingswissenschaft

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Summary

- **Heart rate variability (HRV)** operationalizes the successive beat-to-beat fluctuations over a defined period of time, is derived from the time series of successive R-R intervals using various context-dependent metrics, and reflects the complex dynamic modulation of the heart's chronotropic response to physiological and/or pathological perturbations.
- **HRV metrics are used** as markers of human cardiovascular health and risk stratification, or as measures of load quantification, exercise response and performance, respectively.
- **However, a valid use of HRV in the fields of sports medicine and exercise science** requires careful consideration of the specific measurement principle of the recording device, standardized assessment, preprocessing, analysis, and context-sensitive interpretation.

KEY WORDS:
HRV, Interbeat Intervals, R-R Intervals, EKG, PPG, Autonomic Nervous System, ANS, Sympathetic Activity, Parasympathetic Activity, Monitoring

Introduction and Background

Heart rate (HR) variability (HRV) describes the temporal change (variation) of the heart period or beat-to-beat variability of the HR over a defined measurement period and reflects the dynamic end-organ response of the heart to physiologic and/or pathologic perturbations. The time series of successive R-R intervals is called „tachogram“ from which various metrics with different durations (e.g., from ultra-short-term (~1 min), short-term (~5min) up to long-term (~24 h) depending on the context) are derived (2, 9, 20, 57, 60, 61, 68). HRV is primarily created by the non-linear interaction of the efferent positive chronotropic influence of the sympathetic (SNS, „fight or flight“ response), the negative chronotropic influence of the parasympathetic (PNS, „rest or digest" response) branch of the autonomic nervous system (ANS), and the intrinsic activity of the hearts pacemaker cells and reflects the context-dependent psychoneuroendocrinological modulation of cardiovascular control (8, 42, 48, 71). This complex modulation integrates several feedforward and feedback mechanisms that act on different time scales (e.g., central command, arterial baroreflex, respiratory control, circulating catecholamines, muscle metabo-/mechanoreflex, renin-angiotensin-aldosteron-system) and is therefore related to the dynamic regulation of circulatory control of arterial blood pressure and HR to meet the context-dependent needs of the whole organism. Thus, different evidence-based HRV metrics are used as markers of human cardiovascular health and risk stratification (10, 11, 19, 20, 62, 69) or as measures of load quantification, exercise response and performance, respectively (6, 7, 27, 28). However, for a valid use of HRV in the fields of sports medicine and exercise science careful considerations on standardized assessment, preprocessing, analysis, and context-sensitive interpretation are mandatory.

Assessment and Standardization

A valid and reliable assessment of the time between two successive heartbeats, referred to as the R-R interval in milliseconds, is most crucial for a scientific and practical use of HRV as the R-R interval (based on the detection of the R-wave in the PQRST complex; 31) time series serves as the base for any HRV metric (see figure 1). The gold-standard for R-R assessment is the electrocardiogram (ECG), which allows recordings in the laboratory or during daily activity (up to 24 hours or longer). In addition, several mobile and user-friendly measurement systems and wearables exist, which can record R-R intervals with different applications and form factors (chest strap systems, adhesive patches and electrode systems on the skin) that also utilize electrophysiological, but also optically derived signals such as photoplethysmography (PPG). For valid HRV acquisition through electrophysiological measurements, a sampling rate of at least 250 Hz is recommended to accurately detect the R-peak. Specific analyses show robust results even at lower sampling rate depending on the ›

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Box 1

Potential artifact causes and influencing variables depending on the principle of measurement

Hardware and physiological considerations
- Ectopic beats, atrial fibrillation
- Electrophysiological signal strength
- Measurement site of the application
- Sensor or electrode geometry and contact (pressure)
- Wavelength of light
- Transmission of the light reflection

Software considerations
- Sampling rate
- R-wave detection algorithm
- Preprocessing of data (e.g., detrending method)
- Artefact correction incl. digital filtering (e.g., electrophysiological and motion artifacts)
- Algorithms and default settings of signal processing (e.g., frequency bands)

Considerations of measurement protocol incl. personal and environmental factors
- Resting state or stress / exercise conditions (e.g., intensity, duration, modality)
- Time of day (e.g., morning vs. night) and seasonal effects
- Body position (e.g., lying vs. standing)
- Duration of measurement and chosen HRV metric (time, frequency or non-linear domain)
- Environment (e.g., temperature, humidity, sun and light exposure, hypoxia)
- Age, sex and genetics
- Hormone status (e.g., menstrual cycle, pregnancy)
- Caffeine and alcohol intake
- Medications
- Bladder filling and hydration status
- Nutrition intake
- Health status (e.g., chronic disease, acute viral infection, food poisoning)
- Acute and chronic stressors (e.g., occupation, travel, time shift and jetlag)
- Physical activity and performance level
- Body composition
- Exercise load (e.g., intensity, duration) and recovery status
- Injuries (e.g., impaired mobility) and pain status
- Sleep quality and duration
- Breathing pattern (e.g., paced breathing vs. natural rhythm and free running system)

selected HRV analysis parameters and principle of measurement (14). In order to increase usability and user compliance in field applications, new measurement principles based on PPG are now being used also for HRV assessment during resting conditions. PPG is a simple non-invasive optical technique in which the skin is illuminated by an LED (for example, the flash of a phone) and the reflected amount of light is detected by a photodetector or camera near the light source. The amount of reflected light depends on the volume in the vascular system. After systole the blood volume increases, decreasing the received light intensity, and during diastole the blood volume decreases, increasing the light reflection - therefore, the volume changes can be used to detect the pulse wave (15). The PPG signal can be used to detect HR and HRV - but more specifically, the signal provides pulse rate (PR) and pulse rate variability (PRV). Most commercially available portable devices show a low absolute error under resting conditions, but should always be validated against reference measures to clarify the accuracy of data parameters and maximize real word application value (18, 38). It is essential to evaluate the validity depending on the setting, measurement duration, paradigm and cohort that is investigated (43), because modulators such as the analyzed metric, body position, or individual characteristics of the population can cause deviations in HRV measurements from different devices (18). For applied settings, different portable high-resolution systems have been validated such as chest strap sensor systems for ECG-accurate electrophysiological recordings coupled via Bluetooth connection with receiving devices (smartwatches, smartphone via apps) for acquisition during rest and physical exercise conditions (18). Finally, PPG short-term measurements (metric: RMSSD, see figure 1) with the index finger and smartphone camera (light signal: flashing light) can currently also be recommended depending on the specific solution under resting conditions (3, 52, 66). Other PPG technique form factors like finger rings present promising user-friendly applications for frequent measurements in standardized measuring intervals, e.g., during the night (34).

A clear standardization procedure is essential to avoid and/or correct artifact in collected HRV data for research and practical application (36, 54). This is especially true for ultra-short-term measurements (63). A non-exhaustive list of potential artifact causes and influencing factors (acute and chronic) depending on the measurement principle is shown in Box 1 (4, 16, 19, 21, 40, 42, 44, 58, 70).

HRV Analysis

As shown in Box 1, all HRV assessment technologies are affected by artifacts and/or noise, therefore disclosure of artifact detection/correction methods as well artifact rates (mostly below 5-10%, 64) is mandatory. This is especially true for applied settings that involve different body positions, body movements and physiological strain (see figure 2). Besides the context-sensitive choice of measurement duration, as well as the detection and removal of artifacts (e.g., extra beats, noise, missing beats), HRV analysis software applications should include detrending and interpolation options for R-R time series using transparent algorithms to ensure sufficient data quality and to fulfill signal requirements for further calculation of specific metrics of the time-, frequency-, and non-linear domains (e.g., 64, 67, see supplemental material online, table 1). For the scientific use of automatically calculated HRV metrics in commercially available systems and applications at least raw data access and sufficient information on the above-mentioned preprocessing features as well as the calculated metrics itself should be provided. Cluster scores of different HRV metrics without further information should be treated with caution. As mentioned above when analyzing HRV, reference should always be made to specific HRV metrics of the time-, frequency-, and/or non-linear domains, as these metrics may capture quite different HRV components, and their interpretation is always context-sensitive and depends on the setting (see supplemental material online, table 1, and for recent reviews e.g., 60, 61, 63). Most common linear time- and frequency-domain HRV metrics display rather general descriptive statistical features or display the distribution of the frequency content of the signal (see supplemental material online, table 1). For example, the standard deviation of all normal-to-normal R-R intervals over a given time interval (SDNN) is a general estimate of the global variability of the time series. In addition, the amount of efferent vagal modulation can be estimated from the several parasympathetic-dominated HRV metrics like root mean square of successive differences of NN intervals (RMSSD), High-Frequency (HF) Power, or SD1 from the Poincaré Plot, while metrics from different recording durations may not be used interchangeably and their physiological meaning may vary considerably (36, 61, 68). Although 24h HRV-recordings used to represent the "gold standard" for clinical HRV assessment (62), short-term and ultra-short-term measurements are increasingly used and validated for specific applied settings (63). Further, it should be noted that for several HRV metrics there is still an ongoing debate about their practical relevance and optimal recording lengths as these strongly depend on the algorithm and the setting. E.g., for stable frequency domain metrics, a recording length of two to ten times the wavelength of the lowest relevant frequency component is recommended (9, 68), while this might be partly overcome by more sophisticated time-frequency analysis (41). In addition, several other HRV metrics from e.g., the geometric domain (e.g., HRV triangular index, TINN) were introduced for specific settings (68), but are not frequently used in sports medicine and exercise science. Therefore, the information in table 1 (see supplemental material online) should only be seen as a guideline for a large variety of applications in the field of sports medicine and exercise science.

In addition, R-R fluctuations from short term recordings like RMSSD may show a skewed distribution and very high intra- and inter-individual variation between 10-300 ms (42). Therefore, a logarithmic representation (e.g., lnRMSSD) may help to increase reproducibility, as well as robustness to artifacts (13) and changes in respiratory patterns (51). Further, HRV metrics of the frequency domain such as HF or LF may require additional considerations regarding the calculation method (nonparametric vs. parametric, standard spectral analysis or time-frequency analysis), the calculation (absolute or normalized values with or without consideration of very low frequency, VLF), and the duration of measurement (37, 63, 68). Inconsistent results are often generated using simple ratios, which is therefore discouraged (e.g., the LF / HF ratio may not reliably assess the cardiac sympatho-vagal balance; 12, 42). Insights from non-linear HRV analysis are promising in several clinical and applied settings related to sports medicine and exercise science. As non-linear metrics complement linear HRV and rather focus on (fractal) dynamics and complexity of the time series they might expand our knowledge concerning the behaviour of cardiovascular oscillations in normal healthy conditions as well as in disease states in both resting and exercising conditions (24, 25, 29). However, these measures still need to be further elucidated for a general practical use.

Context-Sensitive Analysis and Interpretation

Singular, absolute values of HRV (e.g., for RMSSD) provide only limited information; this also applies to the comparison with reference values, which is primarily recommended for specific and homogeneous populations (e.g., diseases, age groups; see 1, 46, 56, 58, 70). Comparing a regular intra-individual baseline may help to interpret daily variations in HRV and a rolling average of mean values is favourable for monitoring processes (e.g., 7-day moving average of at least 3 to 5 measurements a week; 13, 22, 49, 50), also in relation to a normal range reference (like

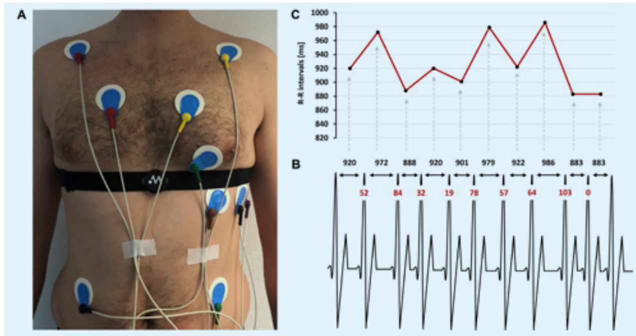

Figure 1

12-channel-ECG and chest strap device (A, from 55), a schematic ECG signal (B) of 11 beats with plotted R-R intervals (in ms, in black) and the respective difference to the next interval (in ms, in red) as raw signal of HRV (mod. from 2), and the resulting R-R interval tachogram (C). Below a few time domain metrics of this HR time series example and the calculation of natural logarithm of RMSSD (lnRMSSD). Mean HR=65 1/min; Mean R-R=925 ms; Minimum=883 ms (68 1/min); Maximum=986 ms (61 1/min); $RMSSD=\sqrt{(mean(52^2+84^2+32^2+19^2+78^2+57^2+64^2+103^2+0^2))}=63$ ms; lnRMSSD=4,14 ms.

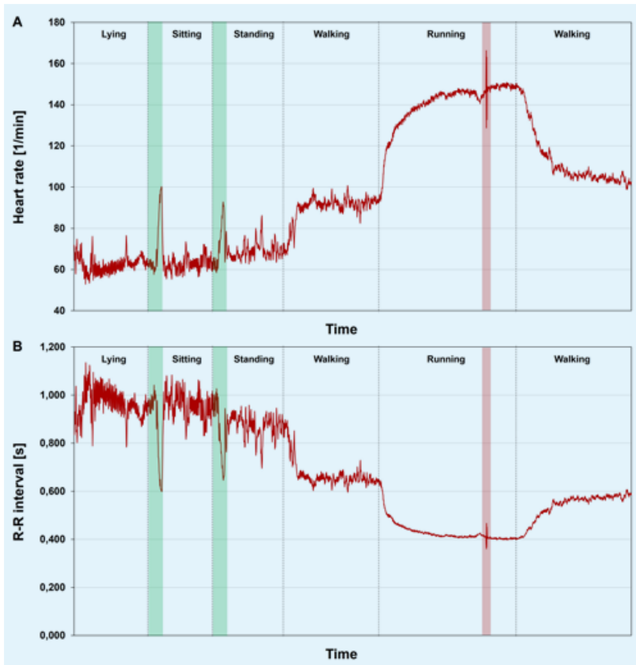

Figure 2

HR (A) and R-R interval tachogram (B) collected with a chest belt device during different conditions; lying (prone), sitting, standing, walking (6 km/h), running (10 km/h) with a following active recovery during walking (6 km/h). It is captured how the variability in the time series decreases with increasing intensity and body position change. Orthostasic reactions due to the active change of position from lying to sitting and from sitting to standing are marked in green. The red area indicates a single artifact due to chest strap movement or an ectopic beat. An ectopic beat is represented by a short R-R interval followed by a compensatory prolonged pause (longer R-R interval). This artifact has little influence on the mean R-R interval and the HR of a 60-second analysis interval, but considerable influence on RMSSD, for example (without artefact correction: mean R-R: 404 ms, HR: 148 1/min, RMSSD: 13,9 ms vs. with artefact correction: mean R-R: 405 ms, HR: 148 1/min, RMSSD: 3,1 ms).

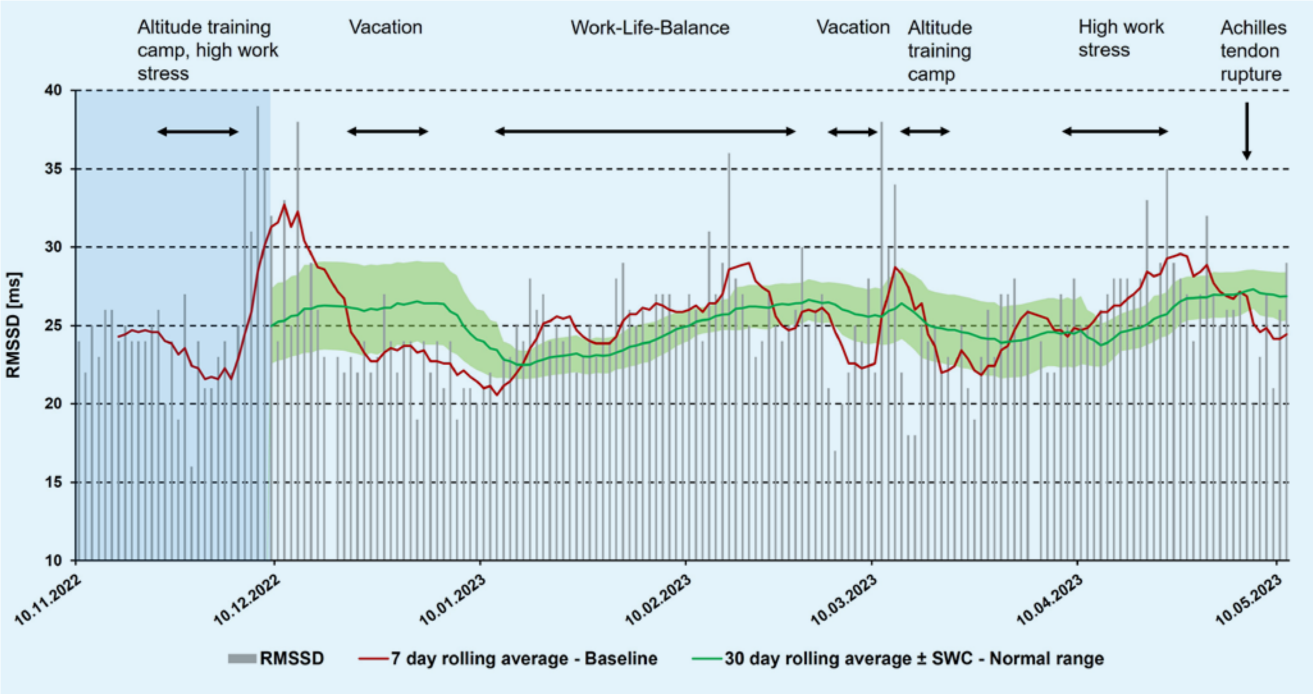

Figure 3

RMSSD data (daily values, in grey) of a 34-year-old male active sports professional over 6 months (PPG during the night), 30-day (initial phase in blue) rolling average as reference for a normal range as smallest worthwhile change (SWC) approach (± SWC: standard deviation x 0.5, in green), and a 7-day rolling average as a baseline (in red). Context annotations in the top of the diagram.

the smallest worthwhile change, SWC) for trend analysis of HRV variations (see figure 3). Further information like resting HR, psychometrical scales and other contextual information may overcome the lack of specificity in the interpretation of HRV values (26, 49). Application of existing standards (e.g., 10, 36, 53, 60, 68) is mandatory to derive appropriate interpretations.

However, higher values (trends) of vagally driven time- and frequency-domain metrics under resting conditions are generally associated with more functionally efficient cardiac autonomic control, whereas HRV declines and becomes more regular with age or disease, revealing a loss of variability and complexity (5, 29, 30, 35, 39, 45). Lifestyle factors (e.g., physical activity, smoking behavior, alcohol consumption, body composition) are associated with adaptations of cardiac vagal function in this context, so a healthy lifestyle can be considered preventive for reducing age-related decline of positive autonomic regulatory dynamics (32). The usefulness of HRV as an indicator of physiological and pathological conditions, for risk stratification (68-70), and as a marker of autonomic adaptive and regulatory capacity (6, 7, 27, 28) is evident. However, longitudinal data recordings are recommended when trend analysis with contextual data is intended. In addition, the reference setting of resting conditions in supine position (68) can be complemented by active orthostatic tests (supine vs. standing), other stress-related conditions like physical exercise, and recovery measurements as these provide additional information on ANS regulation dynamics (23, 24, 28, 36, 65). However, special care must be taken with both HRV assessment and analysis during stress / exercise and recovery as increased non-stationarity, degraded signal-to-noise ratio and additional physiological phenomena (e.g., cardio-respiratory-locomotor-coupling) may complicate its straightforward use and interpretation (28, 42, 59). Considering the mentioned context-sensitive requirements, HRV analysis allows for longitudinal trend analysis of patients (including the potential as a remote digital biomarker; 47) and healthy individuals including athletic and non-athletic populations in various clinical and performance-related settings. This includes the application of HRV monitoring for resting conditions, during and/or after biofeedback and training interventions (e.g., breathing interventions, physiological state analysis, intensity domain delineation), as well as general relationships between recovery status, previous exercise conditions, and symptoms of overreaching and overtraining (6, 7, 27, 28, 33, 42, 62).

Conflict of Interest
The authors have no conflict of interest.

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