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REVIEW

Research Progress in Heart Rate Variability Applications in Exercise Rehabilitation for Cardiovascular Diseases

Zhaoxin Zhu[1], Jianying Shen[1], Yan Zhang[1], Jianren Wang[1], Yujing Sun[1], Weijing Liu[1] and Yawei Xu[1]

[1]Department of Cardiology, Shanghai Tenth People's Hospital, Tongji University School of Medicine, Shanghai 200072, China

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Abstract

Heart rate variability (HRV) is an important marker for assessing the balance of the autonomic nervous system and clinical prognosis, because it can be non-invasively and easily measured, and the results are accurate and valuable. HRV is widely applied in cardiovascular disease fields. Exercise training is an important part of cardiac rehabilitation. Personalized sports rehabilitation therapy can effectively prevent the emergence of cardiovascular diseases, decrease the risk of recurrent cardiovascular events, and ameliorate dysfunction, as well as limitations in life, work, and social participation, caused by adverse cardiovascular events. However, sports rehabilitation can have drawbacks, in that improper training can cause injury, excessive fatigue, or even harmful cardiovascular events. To support future applications, this article reviews recent applications of HRV in sports rehabilitation for cardiovascular diseases.

Keywords: Heart rate variability; autonomic nervous system; cardiac rehabilitation; sports rehabilitation; cardiovascular diseases

Introduction

Heart rate variability (HRV) reflects fluctuations in the heartbeat, which result from the complex interaction between the sympathetic nervous system and the parasympathetic nervous system [1]. A relative decrease in HRV is an independent predictor of cardiovascular disease, including sudden cardiac death and mortality in people middle-aged or older [2]. Increased HRV reflects the body's fitness and adaptability to internal and external stimuli. Many cross-sectional studies have found that people with cardiovascular diseases have lower HRV than those without chronic diseases. Regular sports rehabilitation can decrease the risk of occurrence and recurrence of cardiovascular diseases, as well as the effects of increasing age and body senescence on cardiovascular health [3].

This article is aimed at analyzing the common characteristics of HRV in multiple cardiovascular diseases, and the differential changes in HRV with different forms of exercise. HRV plays a major role in assessing exercise safety and effectiveness in patients with cardiovascular disease.

Correspondence: Yawei Xu and Weijing Liu, Department of Cardiology, Shanghai Tenth People's Hospital, Tongji University School of Medicine, Shanghai, China,
E-mail: xuyawei@tongji.edu.cn; liuweijing98@sina.com

HRV Analysis

Time-Domain Analysis

Frequently used time domain indicators include the standard deviation of all normal to normal (NN) intervals (SDNN), the standard deviation of all 5-minute NN intervals (SDANN), the root mean square value of the continuous difference between adjacent NN interval sequence (rMSSD), the difference between adjacent normal NN intervals greater than 50 ms (NN 50), and the percentage of NN50 with respect to the total number of NN intervals (pNN 50). SDNN reflects the overall balance between the sympathetic and vagal nervous system; SDANN reflects the function of the sympathetic nervous system, and the measured decrease indicates the increase in sympathetic activity; rMSSD and PNN 50 reflect the function of the vagal system; and the measured decrease indicates decreased vagal activity.

Frequency-Domain Analysis

Frequently used domain indicators include total power (TP), high frequency (HF), low frequency (LF), ultra-low frequency (ULF), and very low frequency (VLF). The TP reflects the ability of the autonomic nervous system to regulate the balance of the sympathetic and vagal nerves; HF reflects the regulatory ability of the vagal nervous system; LF reflects the regulatory ability of the sympathetic nervous system, which is substantially regulated by the sympathetic and vagal nerves; LF/HF reflects the balance between the sympathetic and vagal nervous systems; and ULF and VLF are influenced by the circadian rhythm, temperature, peripheral vascular tone, and renin-angiotensin-aldosterone system [4]. Less proportion of ULF and VLF in TP, HRV is usually not analyzed in short-term testing; 24-hour long-term analysis can be used for reference, which lacks a consensus now.

Nonlinear Analysis

Frequently used analysis methods include SampEn, Poincare plots, and detrended fluctuation analysis. Poincare plots are widely applied in clinical practice, and the commonly used indicators are the standard deviation of the normal RR interval, ordinate (SD1) and standard deviation of the normal RR interval, abscissa (SD2). SD1 reflects the function of the vagal system and is associated with baroreflex sensitivity (BRS); SD2 reflects the balance of the cardiac sympathetic and vagal systems, and is associated with LF and BRS.

HRV and Sports Rehabilitation

Sports rehabilitation has clear roles in ameliorating cardiovascular diseases: this therapy improves the arterial endothelial function, regulates the inflammatory immune response, enhances the capacity of skeletal muscle to consume oxygen, and maintains cardiovascular health, thereby improving quality of life and cardiac autonomic nerve regulation function. The balance between the sympathetic and parasympathetic nerves in people with cardiovascular disease differs according to the type of sports rehabilitation. Among people with moderately severe cardiovascular events, regular sports training based primarily on aerobic sports can decrease the risk of cardiovascular disease and all-cause mortality [5].

Respiratory Training

Respiratory muscle training is an important component of sports rehabilitation for cardiovascular diseases. Deep inspiration stimulates stretch receptors, thereby leading to central depression of the medulla and cardiac depression, and affecting the balance of sympathetic and parasympathetic nerves. An increase in respiratory depth and a slowed respiratory rate can improve human autonomic nerve function and adaptability to daily activities [6]. Deep breathing training has been found to inhibit respiratory muscle sympathetic nerve activity and increase vagal nerve activity; this transient vagal predominant breathing pattern can stably increase HRV [7].

People with coronary heart disease often show excessive cardiac sympathetic nerve excitement, thereby potentially resulting in malignant arrhythmia, sudden cardiac death, and other malignant events. Autonomous breathing training can be used as a sports rehabilitation strategy in patients with stable coronary artery disease, to increase vagal activity and/or decrease sympathetic activity, and help maintain or rebuild the balance of the autonomic nervous system. This training can also ameliorate HRV, decrease the load on the heart, and relieve patients' anxiety or other negative emotions [8].

HRV is significantly diminished in people with heart failure, because of cardiac autonomic imbalance. Respiratory muscle weakness further decreases HRV in people with heart failure. Reis et al. [9] have observed the relationships among muscle strength, the function of respiratory muscle, and cardiac autonomic nerve regulation in patients with chronic heart failure, who, in contrast to healthy adults, show impaired cardiac autonomic regulation during rest and DB-M ($P < 0.05$). Significant associations have been observed between inspiratory muscle function (maximum inspiratory pressure) and rMSSD ($r = 0.77$), SDANN (in DB-M, $r = 0.77$), LF ($r = 0.77$), and HF ($r = 0.70$). Thus, respiratory muscle training has profound value in cardiac rehabilitation.

Breathing training, on the basis of the premise of spontaneous breathing control, through the adjustment of breathing rate, breathing amplitude, and the total length of breathing control, can achieve self-healing effects. Training may involve guidance from biofeedback-related equipment.

Aerobic Exercise

People with hypertension have abnormal sympathetic activation and relatively weakened vagus function in the resting state. Masroor et al. [10] have observed the intervention performance of HRV in women with hypertension during a 4-week aerobic exercise program. The exercise group showed increased HFnu, TP, SDNN, and RMSSD ($P < 0.05$), and significantly decreased LFnu, LF/HF ratio, and systolic and diastolic blood pressure ($P < 0.05$). Combined exercise training based on aerobic exercise can enhance cardiac autonomic control. Changes in blood pressure after exercise are associated with resting HRV, particularly in adults with hypertension and parasympathetic depression (i.e., lower SDNN and HFms 2, and higher LF/HF) [11].

After coronary events, the autonomic modulation changes, sympathetic flow increases, and parasympathetic activity decreases. This imbalance may lead to adverse events such as sudden death [12]. Bilińska et al. [13] have conducted a 6 week follow-up in patients performing cycling as aerobic training after coronary artery bypass grafting. The SDNN and HF increased, and LF/HF is decreased in these patients, whereas opposite findings were observed in the control group, thus indicating that decreased sympathetic activity is conducive to parasympathetic activity.

In chronic heart failure, autonomic imbalance, sympathetic activation, and vagal nerve function decreased result from biochemical changes in the central autonomic nucleus as well as altered peripheral autonomic reflex function. Perfusion problems may be compensated for by increasing heart rate and stroke output, thus increasing cardiac output. Abolahrari-Shirazi et al. [14] have observed HRV performance in a 7-week aerobic exercise intervention in patients with left heart failure. A significant difference in SDNN was observed between the experimental group and the control group ($P = 0.003$), and a significant weak correlation was found between ejection fraction and SDNN ($r = 0.279$, $P = 0.047$).

Resistance Training

Resistance training, which maintains or increases skeletal muscle strength and prevents osteoporosis, has recently become a part of maintaining healthy, comprehensive exercise. This training not only prevents the occurrence and progression of cardiovascular disease, but also ameliorates autonomic dysfunction in people with chronic diseases.

During resistance training, the sympathetic nervous system is in an activated state. The influence of resistance training on HRV depends on the type of muscle contraction, the size of the load, the speed of movement execution, the overall time of movement, and the interval time between the two adjacent movement training. Seals et al. [15] have found that, in constant-length training, the muscles can stimulate sympathetic nerve excitation, and Kingsley [16] has observed the same findings in isotonic motion. During the same form of muscle contraction, an increased resistance training load may decrease vagal activity and increase sympathetic activity, in particular, the resistance training of large muscle groups in the lower limbs can further strengthen the sympathetic nerve activity of the subjects compared with the resistance training of the upper limbs [17].

After staged resistance training, the autonomic nerve balance is maintained, and vagal tone is enhanced. Caruso et al. [12] have and observed the HRV performance in patients with coronary heart disease after 8 weeks of 30% 1 RM exercise resistance training. RMSSD, SD1, ApEn, and other indicators increased after exercise, and muscle strength increased during the exercise intervention. Selig et al. [18] have observed HRV during resistance training for 12 weeks in patients with chronic heart failure: the LF and LF/HF values decreased, whereas HF increased, and RMSSD was maintained. Taylor et al. [19] have observed HRV in in older patients with hypertensive disease after upper limb resistance training for 10 weeks. The patients' LF and LF/HF values decreased, whereas the HF increased.

Traditional Qigong

Tai chi, Baduanjin, and other fitness qigong methods are important parts of traditional Qigong. These practices combine meditation, including breathing; slow, gentle, and elegant movements; and aerobic, coordinated, flexible, and balanced movements through multimodal exercise. Traditional qigong regulates the life energy of collateral channels and organs in the body, called "qi." The practice considers the combination of activity and inertia, including shape, spirit, and self-cultivation. Consciousness shifts from a focus on the body and actions to releasing "qi" into the environment without worry or action. Traditional qigong is not only a physical movement but also a spiritual exercise practice. Qigong has a multimodal mode of movement and emotional regulation, and it effectively improves autonomic nervous function in people with cardiovascular disease.

Sato et al. [20] have studied patients with coronary heart disease and observed vagal nerve function after 1 year of tai chi exercise therapy. Significant improvements in vagal nerve function (on the basis of BRS) were observed in patients in the tai chi group ($P = 0.036$). In contrast, the HRV improved with respect to baseline but showed no clear trend. Incorporating tai chi training into cardiac rehabilitation may enhance reflex vagal modulation.

Yu et al. [21] have observed HRV performance in patients with chronic heart failure after a Baduanjin exercise intervention for 12 weeks. SDANN, and SDNN showed significant improvements in the Baduanjin exercise group compared with the control group, and the improvement in HRV was consistent with the results of several cardiac rehabilitation assessments. Zeng [22] has also found lower HR, LF, VLF, VLF, and LF/HF ($P < 0.05$), and higher TP and HF ($P < 0.05$), in patients with hypertensive heart disease than controls, thus indicating that the intervention improved comprehensive autonomic nervous system function and vagal nerve regulation ability.

HRV Guided Exercise Rehabilitation

Analysis of Changes in Exercise Intensity

Safety, effectiveness, and ease of exercise are particularly important in outpatient rehabilitation, community rehabilitation, and home exercise in patients with cardiovascular diseases. Routine heart rate monitoring, blood pressure monitoring, and subjective feeling monitoring during exercise have several limitations. In contrast, HRV can be monitored continuously and non-invasively in real time during exercise, and changes in exercise intensity can be analyzed. The HF value and peak HF frequency show two nonlinear increases with load-increasing exercise, which correspond to the first ventilation threshold (VT1) and the second ventilation threshold (VT2) in respiratory metabolic analysis [23]. Real-time assessment of HRV with a single-lead electrocardiogram (ECG) during cardiopulmonary exercise testing (CPX) facilitates the detection of aerobic exercise thresholds [24].

Ikura et al. [25] have observed patients with heart failure, cardiomyopathy, and coronary artery disease performing CPET (CPET/CPX) increasing load exercise, with the power (WR) adjusted according to the HF value. The authors quantitatively compared oxygen consumption, heart rate, and WR during exercise with the ventilation threshold determined according to CPX. Maintenance of the HF component at 5–10 during exercise was consistent with, and strongly correlated with, the anaerobic metabolic threshold oxygen uptake. Continuous monitoring of HRV HF values during exercise with a wireless cardiac data transmission system provides continuous aerobic exercise intensity measurements and enables the formulation of exercise plans for real-time HRV analysis to help patients with cardiovascular disease.

Prevention of Excessive Exercise

An excessive exercise response is a state of chronic fatigue caused by imbalances among activities of daily life, exercise training, and recovery after exercise [26]. This response can lead to dyspnea, tachycardia, autonomic stress responses, slow recovery of physical and mental state after exercise, and even malignant arrhythmia and sudden cardiac death. Accurate assessment of physical fatigue is essential to prevent physical harm caused by excessive exercise.

HRV analysis can help predict changes in psychological stress and modulation of cardiovascular adaptability throughout the exercise cycle in patients with cardiovascular conditions. Data associated with HRV, such as the mean heart rate sequence (mean HR), NN 50, sSDNN, SDANN, ratio of the total number of all intervals to the height of the histogram (HRVTi), baseline width of the minimum square difference triangular interpolation of the highest peak of the histogram, absolute power of the VLF band, negative natural logarithm of the conditional probability that two sequences will remain similar at the next point (sampen), and SD2, SD1/SD2 ratio are key to assessing physical fatigue [27]. The mean NN interval sequence, SDNN, SDANN, and HRVTi are associated with mental stress levels. With the use of wearable electrocardiogram devices, SD2, and SD1/SD2 can help physicians assess physical fatigue and even the fatigue state during exercise in real time. In addition, during long-term high-intensity exercise, the expected changes in HRV can provide a timely reflection of the physical fatigue level, and the amount of exercise can be adjusted to maintain the exercise program and exercise safety [28].

HRV and Remote Exercise Rehabilitation

HRV Short-Term Detection Technique

Because of limitations in the measurement, analysis, and interpretation of HRV during the remote motion monitoring process, HRV is not widely used in clinical settings. Therefore, international standards for quantitative short-term HRV measurement are an important factor influencing the development of HRV-associated technologies. The standard deviation of the RR interval in 24 hours is an independent predictor of mortality after acute myocardial infarction [29]. Short-term testing can also reflect the association between diminished HRV and cardiac mortality [30]. Short-term HRV testing is more practical and convenient than continuous testing, and consequently is more widely used in the clinical stage to the subsequent rehabilitation stage.

HRV measurements vary with patient position, breathing, and measurement timing. Studies have shown that these variations are associated with the basal heart rate during measurement, and a non-linear relationship exists between the heart rate and RR interval. An increased heart rate leads to a low HRV; therefore, a physiological bias exists when HRV is compared among patients with different mean heart rates [31]. Nunan et al. [32] have conducted a large population study to revise current recommendations and criteria for HRV measurement, quantifying the reference range for short-term HRV measurements in a healthy adult population. Domestic criteria to quantify HRV measurements would be beneficial for patients with CVD who require monitoring and exercise guidance.

HRV and Wearable Devices

The development of wearable technology has facilitated clinical research, exercise rehabilitation, and home monitoring through convenient measurement of various health conditions, exercise guidance, and home rehabilitation. Partially portable equipment has been designed to conveniently record HRV. Although some errors exist in HRV measured by portable equipment and ECG, the measurement results obtained in various living occasions and sports environments have indicated that portable equipment can eliminate the effects of errors and ensure the accuracy of the data [33]. When wearables are used in real life, the cost of the device and the simplicity of HRV measurement should be considered.

HRV and Biofeedback Technology

Biofeedback techniques enable the sensitive sensing of changes in HRV. As applied in the field of chronic diseases, such as cardiac exercise rehabilitation, HRV biofeedback technology can provide guidance regarding the effectiveness and safety of exercise therapy in patients, and corresponding adjustments can be made to an individual's exercise form, exercise intensity, duration, and interval time. HRV biofeedback training can increase cardiac vagal modulation, and potentially decrease the morbidity and mortality associated with cardiovascular diseases, such as arrhythmia, myocardial infarction, heart failure, and other diseases associated with reduced vagal tone [34].

HRV biofeedback technology can regulate the activity of patients' autonomic nervous system function during the exercise and recovery periods. The development of ECG monitoring wearable devices has enabled more convenient exercise monitoring. The use of HRV biofeedback during recovery has been shown to ameliorate cardiac variability (RRmean, SDNN, RMSSD, and LF; $P < 0.01$), shorten recovery times, and decrease subjective fatigue after exercise [35].

Conclusions

HRV has extensive applications in the field of exercise rehabilitation, and HRV monitoring is an effective tool to coordinate the function of exercise rehabilitation and the autonomic nervous system in cardiovascular diseases. On the basis of changes in HRV, exercise training programs for patients with cardiovascular disease can be adjusted, and the occurrence of excessive exercise and malignant cardiovascular events can be prevented. The use of HRV wearable devices supports the safety and effectiveness of remote exercise rehabilitation and home rehabilitation. However, improvements in the anti-dynamic interference ability and sensitivity of HRV monitoring are necessary, and individualized evaluation standards for HRV must be developed to aid in differential disease diagnosis and stratify populations by sports risk. In the future, HRV has great potential as an easily accessible exercise monitoring indicator.

Prospect

HRV testing differs by exercise plan (exercise form, breathing rate, position, etc.), detection equipment, and data analysis method (continuous detection time, data accuracy, etc.); therefore, standardized detection methods are needed. In addition, in exercise detection, the quantification of HRV characteristics in patients with different cardiovascular diseases with varying severity, during rest, warm-up, exercise, and recovery states, aids in the formulation of standardized exercise rehabilitation programs. Few studies have examined HRV and routine exercise rehabilitation tests (blood pressure fluctuation range, blood oxygen saturation, blood lactate concentration, anaerobic threshold, and respiratory compensation point); therefore, further exploration is needed.

Author Contributions

Zhaoxin Zhu: writing – original draft. Jianying Shen, Yan Zhang, Jianren Wang, Yujing Sun, Weijing Liu, Yawei Xu: conceptualization, writing – review and editing, funding acquisition.

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Conflict of Interest

No potential conflicts of interest are reported by the authors.

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