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Progress in heart rate variability and exercise rehabilitation for cardiovascular diseases

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Abstract

Heart rate variability (HRV) is an important marker of assessing the balance and poor clinical prognosis of the autonomic nervous system (ANS) by detecting HRV. Because it is non-invasive, easy to operate, and the result is accurate and visible. It is widely used in the field of cardiovascular disease. Exercise training is an important part of cardiac rehabilitation. Individualized sports rehabilitation can effectively prevent the emergence of cardiovascular diseases, reduce the risk of recurrent cardiovascular events, and improve not only the dysfunction but also the limited life, work, and social participation caused by adverse cardiovascular events. However, sport is also a double-edged sword, improper training will cause sports injury, excessive fatigue, and even malignant cardiovascular events. This paper reviews the application of HRV in sports rehabilitation for cardiovascular diseases in recent years, providing a reference for the further application of HRV in the field of sports training in cardiac rehabilitation.

Keywords

Heart rate variability, autonomic nervous system, cardiac rehabilitation, sports rehabilitation, cardiovascular diseases

Introduction

Heart rate variability（HRV） reflects the fluctuation between continuous heartbeat, which is the result of the complex interaction between the sympathetic nervous system and the parasympathetic nervous system[1]. The relative reduction in HRV is an independent predictor of cardiovascular disease, including sudden cardiac death and the mortality in middle-aged and elderly people[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 compared with those without chronic diseases. Regular sports rehabilitation can reduce the risk of occurrence and recurrence of cardiovascular diseases, and reduce the effects of increasing age and organic senescence in cardiovascular health[3].

This paper reviews aims to analyze the common characteristics of HRV in multiple cardiovascular diseases, and the differential alteration of HRV under different forms of exercise. So as to achieve, HRV plays a greater role in exercise safety and effectiveness in patients with cardiovascular disease.

1.The HRV analysis

1.1 Time-domain analysis

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Frequently-used time domain indicators: 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 throughout the entire process (rMSSD), the number of that the difference between adjacent normal NN intervals is greater than 50 ms (NN 50), and the percent of NN50 in 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, 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.

1.2 Frequency-domain analysis

Frequently-used domain indicators: 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 mainly reflects the regulatory ability of the vagal nervous system; LF mainly reflects the regulating ability of the sympathetic nervous system, which is substantially regulated by the combined sympathetic nerve and the vagus nerve; LF / HF reflects the balance between the sympathetic nerve and vagus nervous system; ULF and VLF are mainly influenced by the circadian rhythm, temperature, peripheral vascular tone, and the renin-angiotensin-aldosterone system[4]. In the relatively low total power, HRV is usually not analyzed in short-term testing, 24-hour long-term analysis can be used for reference, but there is no unified conclusion at present.

1.3 Nonlinear analysis

Frequently-used analysis methods: SampEn, Poincare plot, Detrended fluctuation analysis (DFA), etc. At present, the Poincare plot is widely used in clinical practice, and the commonly used indicators are SD1 (standard deviation of normal RR interval, ordinate) and SD2 (standard deviation of normal RR interval, abscissa). SD1 mainly reflects the function of the vagus al system and it is associated with baroreflex sensitivity (BRS); SD2 mainly reflects the balance of the cardiac sympathetic and vagal system and is associated with LF and BRS.

2.HRV and the sports rehabilitation program

The role of sports rehabilitation in improving cardiovascular diseases is obvious to all, which profits improves the arterial endothelial function, regulates the inflammatory immune response, enhances the oxygen intake capacity of skeletal muscle ,and maintains cardiovascular health. And then it will improve the quality of life and cardiac autonomic nerve regulation function of cardiovascular people. The balance between the sympathetic and parasympathetic nerves in patients with cardiovascular disease will be changed according to the form of sports rehabilitation. Among people with moderately severe cardiovascular events, regular sports training mainly based on aerobic sports can reduce the risk of cardiovascular disease and all-cause mortality[5].

2.1 Respiratory training

Respiratory muscle training is an important component of sports rehabilitation for cardiovascular diseases. Deep inspiration stimulates stretch receptors, leading to central depression of the medulla and cardiac depression, which affects the balance of sympathetic and parasympathetic nerves. The increase in respiratory depth and the slow down of respiratory rate can improve the human autonomic nerve function and

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improve the adaptability to daily activities[6]. Studies have shown that deep breathing training can inhibit respiratory muscle sympathetic nerve activity and increase vagal nerve activity, and this transient vagal predominant breathing pattern can increase HRV more stably[7].

Patients with coronary heart disease often show excessive excitement of the cardiac sympathetic nerve, which may induce the occurrence of a 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 (SCAD), to increase vagal activity and/or reduce sympathetic activity and help maintain or rebuild the balance of the plant nervous system. It also can improve the variability of heart rate, reduce the load on the heart and relieve patients anxiety or other negative emotions[8].

HRV is significantly reduced in patients with heart failure due to cardiac autonomic imbalance, and respiratory muscle weakness will further reduce HRV in patients with heart failure. Reis Michel Silva et al.[9]searched chronic heart failure patients (CHF) and observed the relationship between muscle strength and function of respiratory muscle and cardiac autonomic nerve regulation. The results showed that CHF patients showed impaired cardiac autonomic regulation during rest and DB-M compared with healthy adults ($p < 0.05$). There were significant associations between the function of the inspiratory muscle (maximum inspiratory pressure) and rMSSD ($r = 0.77$), SDANN (in DB-M, $r = 0.77$), LF ($r = 0.77$), and HF ($r = 0.70$). Respiratory muscle training is of profound value in cardiac rehabilitation.

Breathing training, which under 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, and it can also be trained under the guidance of biofeedback-related equipment.

2.2 Aerobic exercise

Hypertension patients have abnormal sympathetic activation and relatively weakened vagus function in the resting state. Masroor Sidra et al.[10] took female hypertensive patients as a research subject, and observed the intervention performance of HRV during a 4-week aerobic exercise. The results showed increased HFnu, TP, SDNN, and RMSSD in the exercise group ($p < 0.05$), along with significant decreases in LFnu, LF / HF ratio, systolic and diastolic blood pressure ($p < 0.05$). Combined exercise training based on aerobic exercise can enhance cardiac autonomic control. And the change in blood pressure after exercise is associated with resting HRV, especially in adults with hypertension and parasympathetic depression (i.e., lower SDNN and HFms 2, and higher LF / HF)[11].

After coronary events, autonomic modulation will be changing, the sympathetic flow will be increasing and the parasympathetic activity will be decreasing, this imbalance will lead to the occurrence of adverse events such as sudden death[12]. Bilinska M et al.[13] took patients after coronary artery bypass grafting as a research subject. The time of follow up was 6 weeks and the method of aerobic training is cycling, The results showed SDNN and HF are increased, and LF / HF is decreased (which is opposite to the control group), indicating decreased sympathetic activity conduce to parasympathetic activity.

In chronic heart failure, autonomic imbalance, sympathetic activation, and hypo vagus result from biochemical changes in the central autonomic nucleus as well as altered peripheral autonomic reflex function. Perfusion problems can be compensated by increasing heart rate and stroke output, thus improving cardiac output. Abolahrari-Shirazi S et al[14] took patients with left heart failure as a research subject. They observed the performance of HRV in a 7-week aerobic exercise intervention. The results showed a significant difference in SDNN between the experimental group and the control group ($P=0.003$) and a significant weak correlation between ejection fraction and SDNN ($r=0.279$, $P=0.047$).

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2.3 Resistance Training

Resistance Training(RT), which maintains or increases skeletal muscle strength and prevents osteoporosis, has recently become a part of maintaining healthy and comprehensive exercise. It can not only prevent the occurrence and progressive progression of cardiovascular disease but also improve autonomic dysfunction in people related to chronic diseases.

During resistance training, the sympathetic nervous system is in an activated state. The influence of resistance training on HRV will be changed by the type of muscle contraction, the size of the load, the speed of movement execution, the overall time of movement, and the time of rest between groups. Seals et al.[15] said that in the process of constant-length training, muscles can stimulate sympathetic nerve excitation; Kingsley[16] said it is the same in the process of isotonic motion. In the same form of muscle contraction, an increase the load of resistance training may reduce vagal activity and increase sympathetic activity, especially the resistance training of large muscle groups of the lower limbs, which can further enhance sympathetic activity relative to the upper limbs[17].

After staged resistance training, the balance of the autonomic nerve is maintained and the vagal tone is enhanced. Caruso et al.[12] studied patients with coronary heart disease and observed the HRV performance under 8 weeks of 30% 1 RM exercise resistance training. The results showed that the increase of RMSSD, SD1, ApEn, and other indicators increased after exercise, and muscle strength is improved compared with that before exercise intervention. Selig et al.[18] studied patients with chronic heart failure and observed HRV during resistance training for 12 weeks. The results showed decreased LF, LF / HF values, increased HF, and maintained RMSSD. Taylor et al.[19] studied elderly patients with the hypertensive disease, observed theirs' HRV under upper limb resistance training for 10 weeks, and the results showed that LF, LF / HF values decreased and HF increased.

2.4 Traditional qigong

Tai Chi, Baduanjin, and other fitness Qigong are important parts of traditional Qigong. They combine meditation, including breathing, slow, gentle, and elegant movements, and aerobic, coordinated, flexible, and balanced movements, which belong to the multi-mode exercise mode. Traditional Qigong can regulate the life energy of collateral channels and organs in the body, or it is called "qi".It pays attention to the combination of activity and inertia, both shape and spirit and self-cultivation. Its consciousness shifts from focusing on the body and actions to releasing it into the environment without worry or action. Traditional Qigong is not only a physical movement but also a spiritual exercise. It is precise because of the emotional relief and multimodal exercise mode, it can effectively improve the autonomic nervous function in patients with cardiovascular disease.

Sato Shinji et al.[20] studied patients with coronary heart disease and observed the vagal nerve function after the one-year Tai Chi exercise therapy. The results showed that the improvement of vagal nerve function (BRS) of patients in the Tai Chi group was statistical significance ($P = 0.036$).On the other hand, HRV improved from baseline but showed no obvious trend. Combining with Tai Chi training during cardiac rehabilitation may enhance reflex vagal modulation.

Meili Yu et al.[21] studied patients with chronic heart failure and observed the HRV performance in Baduanjin exercise intervention in 12 weeks. The results showed that compared with the control group, SDANN, and SDNN were significantly improved in the Baduanjin exercise group, and the improvement of HRV was consistent with the results of several cardiac rehabilitation assessments. Zeng Fei[22]also found that in hypertensive heart disease, the HR, LF, VLF, VLF, and LF / HF were lower than the control group ($P < 0.05$), and TP and

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HF were higher than those of the control group ($P < 0.05$), indicating that the intervention could improve the comprehensive function of the autonomic nervous system and the regulation ability of vagal nerve.

3.HRV guided exercise rehabilitation

3.1 Analyze the changes in exercise intensity

The safety, effectiveness, and ease of exercise are particularly important in outpatient rehabilitation, community rehabilitation, and home exercise of patients with cardiovascular diseases. Routine heart rate monitoring, blood pressure monitoring, and subjective feeling monitoring during exercise have certain limitations. HRV can continue, non-invasive, and real-time monitor exercise and analyze the change in exercise intensity. The study showed that the HF value and peak HF frequency (fHF) had two nonlinear increases in load-increasing exercise, which corresponds to the first ventilation threshold (VT1) and the second ventilation threshold (VT2) in the respiratory metabolic analysis[23]. Real-time assessment of HRV by a single-lead ECG during CPX facilitates the detection of aerobic exercise thresholds[24].

Hidehiko Ikura et al.[25] took patients with heart failure, cardiomyopathy, and coronary artery disease as a research subject, and observed that during CPET（CPET/CPX）, within the increasing load exercise, according high frequency (HF) HF value to adjust the power (WR). And then quantitatively compare the oxygen consumption (VO2), heart rate (HR), and WR during exercise with the certain ventilation threshold (VT) determined by cardiopulmonary exercise test (CPX). The results showed that maintaining the high frequency (HF) component: 5-10 during exercise was consistent with the anaerobic metabolic threshold oxygen uptake, and there was a strong correlation between them. Continuous monitoring of HRV HF values during exercise using a wireless cardiac data transmission system can help patients with cardiovascular disease to provide continuous aerobic exercise intensity measurements and formulate exercise plans for real-time HRV analysis.

3.2 Prevent excessive exercise

Excessive exercise response is a chronic state of fatigue caused by imbalances among activities of daily life, exercise training, and recovery after exercise[26]. It can lead to the occurrence of dyspnea, tachycardia, autonomic stress response, slow recovery of physical and mental state after exercise; and even the occurrence of malignant events such as arrhythmia and sudden cardiac death. An 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 cardiovascular patients. Some data related to HRV such as Mean of heart rate sequence(meanHR)、The number of that the difference between adjacent normal NN intervals is greater than 50 ms(NN 50)、Standard deviation of all normal to normal NN intervals(SDNN)、The standard deviation of all 5-minute NN intervals(SDANN)、Ratio of 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(TINN)、Absolute powers of VLF band(aVLF)、Negative natural logarithm of the conditional probability that two sequences remain similar at the next point(sampen)、Standard deviation of normal RR interval, abscissa(SD2)、Ratio of SD1 to SD2(SD1/SD2) are the main keys to assessing physical fatigue[27]. Mean of NN interval sequence(MeanNN)、SDNN、SDANN and HRVTi are related to the level of mental stress in the subjects. Under the condition of combining wearable electrocardiogram devices, SD2、SD1/SD2 can help doctors to assess physical fatigue, even they can real-time assess the fatigue state during exercise. In addition, during long-term high-intensity exercise, the expected changes in HRV can timely reflect the

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physical fatigue level, and then adjust the amount of exercise to maintain the exercise program and exercise safety[28].

4.HRV and remote exercise rehabilitation

4.1 The HRV short-term detection technique

Some of the limitations in the measurement, analysis, and interpretation of HRV during the remote motion monitoring process make it still not widely used in the clinical setting. Therefore, the domestic standards for quantitative short-term HRV measurement are an important factor affecting the development of HRV-related 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 reduced HRV and cardiac mortality[30]. Short-term HRV testing is more practical and convenient than continuous testing, so it is more widely used in practical work.

HRV checking will vary with patients' position, breathing, and measurement timing. Studies have shown that this is related to the basal heart rate during measurement, and there is a non-linear relationship between heart rate and RR interval. When the heart rate increases, it will lead to a low HRV, so there is a physiological bias when comparing HRV in patients with different mean heart rates [31]. Nunan D et al.[32] 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 more beneficial for patients with CVD who need monitoring and exercise guidance.

4.2 HRV and wearable devices

The development of wearable technology provides clinical research, exercise rehabilitation, and home use with convenient measurement of various health conditions, exercise guidance, and home rehabilitation. Partial portable equipment have been designed to conveniently record an HRV. Although there are some errors in HRV measured by portable equipment and electrocardiograms (ECG), the measurement results obtained in various living occasions and sports environments show that a small number of absolute errors can be accepted[33]. When wearables are used in real life, the cost of the device and the simplicity of HRV measurement should be considered.

4.3 HRV and the biofeedback technology

The Biofeedback technique enables the sensitive sensing of changes in HRV. When it applied in the field of chronic diseases such as cardiac exercise rehabilitation, HRV biofeedback technology can provide certain guidance on the effectiveness and safety of exercise therapy in patients, and even make corresponding adjustments to the individualized exercise form, exercise intensity, duration, and interval time of patients. According to HRV biofeedback training, it can increase cardiac vagal modulation, and maybe reduce 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 exercise and recovery periods, and with the development of ECG monitoring wearable devices, it is more convenient to achieve the purpose of exercise monitoring. Related studies showed that the use of HRV biofeedback during recovery improved cardiac variability (RRmean, SDNN, RMSSD, and LF; $p < 0.01$), shortened recovery time, and reduced subjective fatigue after exercise[35].

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Conclusions

To sum up, HRV has great 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. The changing trend of HRV can adjust the exercise training program of patients with cardiovascular disease and prevent the occurrence of excessive exercise and malignant cardiovascular events.Under the condition of combining HRV wearable devices, the safety, and effectiveness of remote exercise rehabilitation and home rehabilitation are supported.However, it is also necessary to improve the anti-dynamic interference ability and sensitivity of HRV monitoring, and to develop individualized evaluation standards for HRV to distinguish different disease diagnosis and different sports risk stratification populations. In the future, HRV has great potential to serve as an easily accessible indicator of exercise monitoring.

Prospect

HRV testing is different in exercise plan (exercise form, breathing rate, subject position, etc.), detection equipment, and data analysis methods (continuous detection time, data accuracy, etc.), so standardized detection methods need to be unified. In addition, in the process of exercise detection, the quantification of HRV characteristics of different severity and different cardiovascular diseases in rest, warm-up, exercise, and recovery state is conducive to the formulation of the standardized exercise rehabilitation program. There are few studies on HRV and routine exercise rehabilitation tests (blood pressure fluctuation range, blood oxygen saturation, blood lactate concentration, anaerobic threshold, and respiratory compensation point), and 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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