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Information-based Similarity as Novel Heart Rate Variability Indices in Congestive Heart Failure Assessment

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Abstract

The attack of congestive heart failure often acts on the patient's vagus nerve and sympathetic nerve, leading to the decline of cardiac regulation function, thereby inducing sudden death and other diseases. Although the traditional analysis method based on time and frequency domain has some feasibility, it ignores the physiological characteristics such as autonomic nervous rhythm. Therefore, this paper combined with information similarity method to analyze the characteristics of short-term fluctuation of heart rate in patients with chronic heart failure. By calculating the IBS index and the ratio of high and low frequencies of 98 patients and normal subjects, the results is analyzed and screened for significance. It is found that the IBS index of patients and normal subjects is significant (P <0.001), and the screening accuracy can reach 75%, and the sensitivity and specificity are maintained at a high level. In addition, when IBS index is combined with LH, the screening accuracy can reach 87.8%, which is increased by 9.2% compared with the traditional screening index LH. Therefore, IBS index provides a new perspective for the screening of CHF disease and has great clinical potential.

Keywords

CHF; HRV; IBS; LH.

1. Introduction

Congestive heart failure (CHF) is a common and progressive disease in the department of cardiology. It is a clinical syndrome with left ventricle filling and reduced ejection fraction caused by changes in heart structure and function. Repeated attacks will reduce patients' daily living ability, lead to limited social activities, and further seriously decrease patients' quality of life [1]. Chronic heart failure occurs when the heart muscle becomes less able to contract under the influence of disease, resulting in a shortage of blood for the heart to beat, it cannot satisfy the body namely normal need organization metabolism demand. This can lead to a variety of diseases, including heart valve disease, coronary arteriosclerosis and other chronic lung diseases. In clinical environment, chronic heart failure is a complex syndrome group. The causes of the disease come from many aspects, that is, two or more kinds of diseases lead to heart damage. Therefore, it need early diagnosis, early treatment.

The onset of heart failure is often accompanied by autonomic nervous dysfunction, which is often manifested in decreased vagal nerve excitability and significantly increased sympathetic nerve tone, leading to insufficient cardiac regulation function. HRV (Heart Rate Variability) is an important indicator to evaluate autonomic nervous function. Heart rate variability (HRV) signals extracted from electrocardiogram (ECG) are widely used to evaluate autonomic nervous system activity in heart failure studies [2]. Several HRV indicators have been used in the study of heart failure, because HRV analysis is a non-invasive and useful tool to reflect the state of the autonomic nervous system [3-5]. Currently, it is believed that heart rate variability plays an important role in the judgment of the condition of heart failure patients and the evaluation of the efficacy, and it can reflect the degree of heart rate fluctuation. Decline in heart rate variability suggests decreased vagal tone or increased sympathetic tone, and these can increase the risk of sudden death. Therefore, the index of heart rate variability can effectively predict the sudden death and severity of disease in patients with chronic heart failure. At the same time, the value can also reflect the dynamic balance degree of parasympathetic nerve and sympathetic nerve in cardiovascular regulation, and the analysis of this index can understand the activity of sympathetic nerve and parasympathetic nerve [6]. Traditionally, the separation method of HRV is mainly in the time domain and frequency domain. Takese et al. found that the time-domain HRV index value of CHF subjects was significantly lower [7]. Binkley et al. showed that the frequency domain HRV index reflects changes in the ANS and significant differences between healthy and CHF subjects [8]. Yu et al. reported that the frequency domain index helps to distinguish CHF subjects from healthy subjects [9].

Although this method are work in some aspects, it ignores the short-term fluctuation characteristics of heart rate and autonomic nervous rhythm, and brings some errors to the experimental results. Therefore, this paper analyzes the regularity of heart rate fluctuation in patients with chronic heart failure based on information similarity IBS algorithm. IBS method is based on rank frequency analysis of acceleration/deceleration patterns of heart rate fluctuations, which can effectively classify them according to the information content of symbol sequences. It has been fully described and validated the method [10], and applied to the heart rate time series, the literature text and genetic sequence [11,12] based on the similarity of information, considering the dynamic nonlinear characteristics of ECG signal, can effectively eliminate the sympathetic nerve and parasympathetic nerve antagonism effect caused by the inherent noise characteristics, through comparing the IBS value of patients and healthy people. It is feasible to reflect the information contained in the time series and analyze the similarity between the two kinds of samples in order to explore the physiological mechanism of CHF.

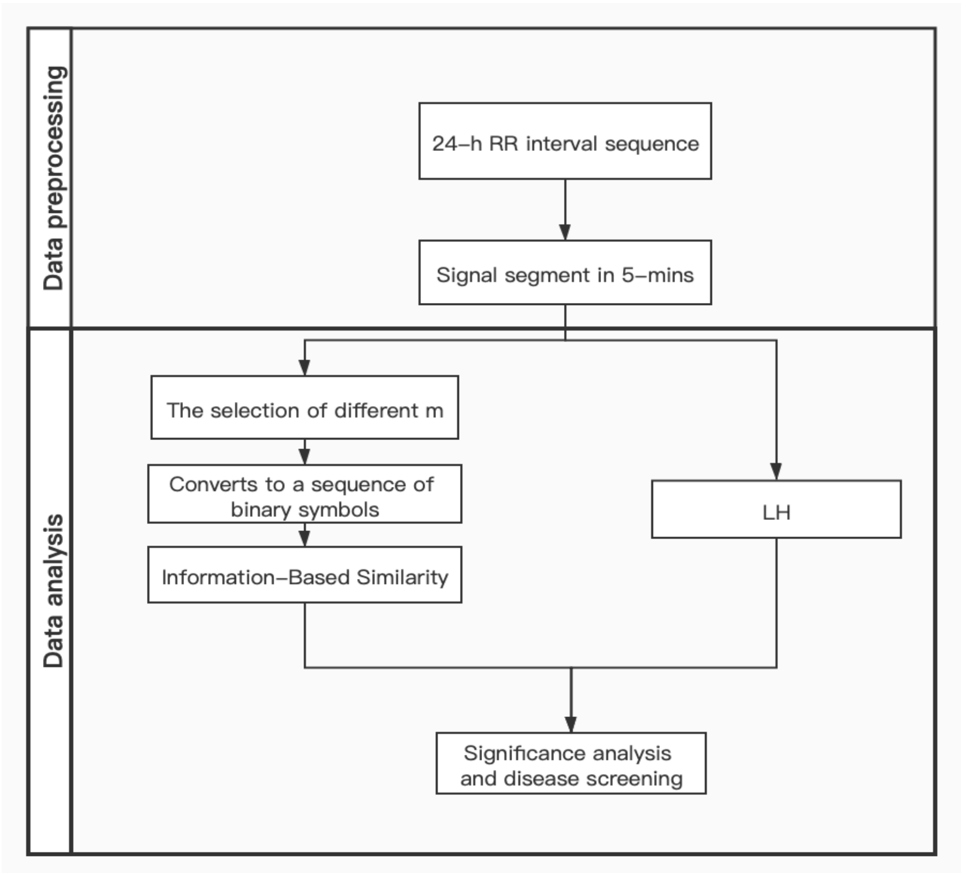

Fig. 1 Scheme of Information-Based Similarity (IBS)

This paper intends to analyze chronic heart failure based on IBS and verify the results with the high-low-frequency ratio, so as to achieve the purpose of improving the diagnostic rate. The experimental process is shown in Figure 1. Taking its upward or downward trend as the dividing standard, combined with the influence of parameter fluctuations on accuracy, a series of calculation formulas are used to convert it into binary sequence. The ordered patterns in this series of sequences are detected and quantified, and then converted into symbol sequences. Finally, the distance between fragments, namely information similarity, is calculated as the eigenvalue and the feature screening is carried out. At the same time, the high and low frequency ratio of the traditional index reflecting the balance of autonomic nerve is calculated to verify and supplement each other with the information similarity, and the patients with chronic heart failure are analyzed and screened together.

2. Analysis Method of Heart Rate Variability(HRV) Based on IBS

2.1 Introduction of used data and preprocessing method

Our project used data coming from the public ECG signal data set provided by PhysioNet website. We selected information from 98 volunteers (54 patients and 44 normal people) to analyze the 24-hour RR interval data set and excluded the error data longer than 3S to ensure the purity of our data and preliminary processing to prevent noise interference.

2.2 Feature Extraction

In this project, we hope to extract sample data features as significantly as possible through effective methods to improve the accuracy and significance of the experiment.

Although the traditional high/low frequency ratio (LH) method has some drawbacks like unstable and inaccurate, it is a classical index and can be used as a contrast, so the above two methods are used for feature extraction.

2.2.1 IBS

Information-similarity proposed by Cui and their team [13] can measure the "distance" between two groups of symbol sequences to determine the difference of repetition patterns in two groups of symbol sequences, so as to further analyze the potential dynamics and practical significance behind this similarity.

In order to analyze the regularity of short-term heart rate (HR) fluctuation in patients with chronic heart failure, we first divided each RR interval sequence into a series of non-overlapping 5-minute RR segments (RRs). Then the complex physiological sequence is transformed into binary sequence, and then into symbol sequence. The distance between two groups of symbol sequences is calculated, which is known as IBS index.

The specific steps of calculation are as follows:

Step 1: The decrease and increase of RR interval are represented by 0 and 1 respectively.

$$I_n = \begin{cases} 0, & RR_n \le RR_{n-1} \\ 1, & RR_n > RR_{n-1} \end{cases}$$

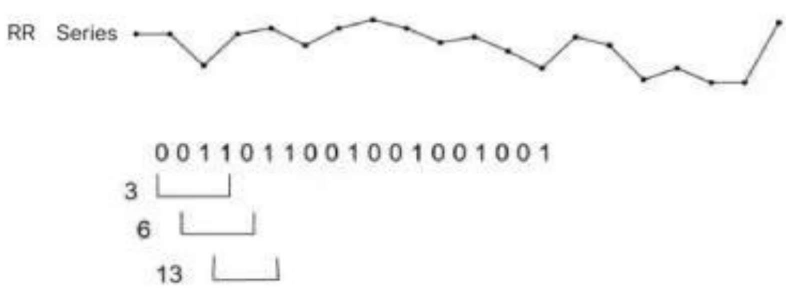

Fig. 2 4-byte letter (M = 4) conversion diagram

For continuous n-length RR sequences, we can get a binary sequence with corresponding length of n-1, and then convert each m-byte binary number into an m-byte letter. Each m-byte letter which can represent 2^m fluctuation patterns in total represents a special RR interval fluctuation pattern. For a given RR interval sequence, if the sliding window is 1 each time, a series of m-byte letters can be obtained. We can use such a series of m-byte letters to reflect the potential dynamic information of the original RR sequence.

By analyzing the distribution of these letters, we can diagnose the state of each individual's physiological system.

Step2: These m-byte letters are sorted according to the number of occurrences. If the number of occurrences of the letters is the same, they are sorted according to the inherent order of the letters. For two groups of m-byte letter sequences, we define the distance d (I1,I2) as:

$$N = \sum_{i=1}^{L} [-p_1(w_i) \log p_1 (w_i) - p_2(w_i) \log p_2 (w_i)]$$

N is the normalization factor, L represents the total number of different m-bit letters, and represents decimal m-bit letters, such as 3, 6, 13. P is the probability of appearance with the letter.

$$S(w_i) = \frac{[-p_1(w_i) \log p_1 (w_i) - p_2(w_i) \log p_2 (w_i)]}{N}$$

$$D(R_1, R_2) = \frac{1}{L} \sum_{i=1}^{L} |r_1(w_i) - r_2(w_i)| \, S(w_i)$$

D represents the IBS value of two adjacent RRs, and R represents the order of letters. The value of IBS index reflects the similarity of HR fluctuation in records. The smaller the value is, the greater the similarity is, and vice versa. In this experiment, we calculate the average IBS value of all the two adjacent minutes of the experimental individually, which is recorded as the individual's IBS value.

2.2.2 High low frequency ratio

Frequency domain analysis is often used to analyze the evaluation process of heart rate variability. The low frequency energy LF of HRV signal is closely related to sympathetic activity, while the high frequency energy HF can reflect parasympathetic activity. High low frequency ratio (LH) can reflect the tension balance of sympathetic nerve and parasympathetic nerve. It is an important indicator of autonomic nerve function and is widely used in the analysis and screening of various diseases [14]. By using fast Fourier transform in the RR interval, it is not difficult to obtain the power spectrum, so as to distinguish the components of different frequency domains. The low-frequency energy LF (0.04 ~ 0.15 Hz) and high-frequency energy HF (0.15 ~ 0.4 Hz) can be calculated, and the high-frequency to low-frequency ratio can be obtained in this way.

$$LH = \frac{LF}{HF}$$

2.3 Index evaluation

We choose T-test to analyze significance. T-test is first proposed by W.S.OOSSET in 1905. T is the standard error (SX) between the sample mean SX (x) and the population mean. T test is used to compare the difference between two means. At the same time, Fisher Discriminant function is introduced to screen the accuracy.

3. Results

3.1 Significance analysis

As shown in Figure 3, the information similarity IBS and high low frequency ratio LH of normal people are significantly higher than those of CHF patients. The IBS index of normal people is significantly higher than that of CHF patients. At the same time, compared with healthy subjects, the high to low frequency ratio of CHF patients is significantly lower than that of normal subjects.

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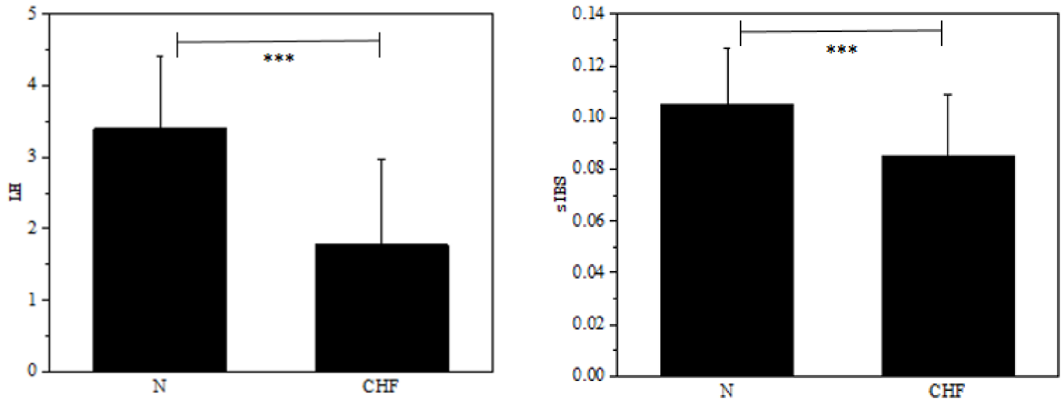

(A) (B)

Fig. 3 Indices for normal (N) and congestive heart failure (CHF) groups. (A) LH, (B) sIBS, ***represent p<0.001

3.2 Selection of letter length parameter m

When calculating the information similarity IBS of samples, the selection of length parameter m is very important, which determines that a letter is composed of several binary numbers. The calculated IBS index is often very different with different length parameters. Therefore, it is necessary to choose an appropriate m value.

Considering that the type of letters cannot exceed the minimum number of RR intervals in one minute, and the RR interval per minute of the data after preprocessing is [20, 173], we calculate M = 2-8 in the process of processing to screen patients with CHF. Figure 4 shows the IBS index calculated according to different m values as the criterion, and the accuracy (ACC) calculated by SPSS classification is the proportion of correctly classified samples.

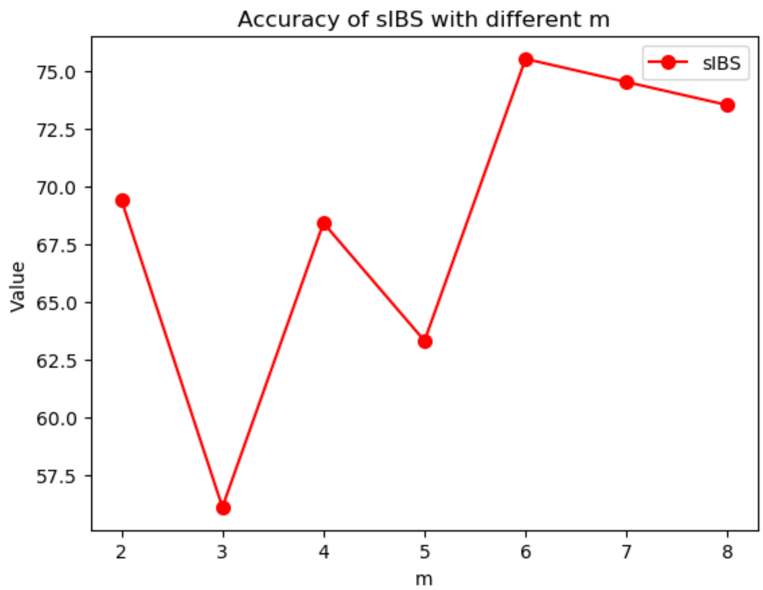

Fig. 4 Statistical significance of sIBS with different m

As can be seen from Figure 4, for the 98 data used in this experiment, there are some differences in the screening accuracy obtained by using different features. When m = 6, the calculated sibs index achieves the maximum screening accuracy for sample classification. Finally, we chose M = 6, that is, the number of binary elements in the alphabetic sequence is 6. At this time, IBS is used to screen

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CHF patients more accurately. It also provides a new way for clinical diagnosis of patients with chronic heart failure.

3.3 Screen of CHF

We combine these two indicators to screen patients with CHF, that is, using SPSS classification calculation to screen healthy samples and CHF to screen samples of patients. The results are shown in Table 1. For the experimental samples in this experiment, the screening accuracy ACC, sensitivity Sen and specificity SPE obtained by using different characteristics and combination methods are different. The classical index LH is similar to the IBS index in the single index screening of CHF. When the sibs index is combined with the high and low frequency ratio LH, the screening accuracy has been significantly improved, achieving the highest screening accuracy (ACC = 87.8%), which is 9.2% higher than the traditional screening index LH. At the same time, the sensitivity is improved compared with single index, and the specificity is kept at a high level of 94.4%. Therefore, in CHF screening, the combination of high and low frequency ratio and information similarity can obtain more accurate results.

Table 1. Experimental samples

when m=6,COMPARION BETWEEN SCREENING RESULTS OF NON-CHF AND CHF GROUPS

Indices	non-CHF	CHF	Acc/%	Sen/%	Spe/%	p-value
LH	3.545±1.335	1.240±0.150	78.6	75.9	81.8	0.000
IBS	0.118±0.016	0.090±0.046	75.5	75.9	75.0	0.000
IBS+LH	3.663±1.351	1.330±0.196	87.8	94.4	79.5	0.000

LH:the ratio of low-frequency power to high-frequency power,

IBS:information-based similarity,

Acc:accuracy, Sen:sensitivity, Spe:specificity.

4. Analysis and discussion

4.1 Comparison and Analysis

Chronic heart failure is a complex clinical syndrome caused by complex factors. It is known as slow in development and progress. In addition to the obvious symptoms such as dyspnea and cough, it is often caused by sympathetic nervous system.

The abnormal autonomic nervous function caused by stimulation can be reflected in the heart rate characteristics. Because of the pathological characteristics, we can monitor the health status of the body and strengthen the prevention of such diseases by detecting the heart rate changes.

In the specific analysis and research, we use the high and low frequency ratio, which is a recognized and effective means to evaluate the ANS index. We improve and verify the validity of LH index in our project. The ratio of high frequency to low frequency of samples with the characteristics of chronic heart failure was significantly higher than that of the control group. In our experiment, the single index prediction accuracy of LH is 78.6%.

But we didn't stop here. We tried and analyzed again and found another convincing index: IBS (information similarity) was also satisfactory in this experiment, so we made a new attempt. IBS index also had good discrimination significance between patients and controls ($P < 0.01$), significance ($P < 0.001$) combining LH and IBS could get more ideal results, and the discrimination accuracy of samples and controls was improved to 87.8%.

It can be seen that the introduction of IBS index into the determination of chronic heart failure, together with LH index, can significantly improve the accuracy and significance, and make progress in the screening of chronic heart failure.

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4.2 Physiological Significance

Chronic heart failure is a chronic cardiovascular syndrome, accompanied by ANS dysfunction and instability pattern [14]. In this project, we measured the differences of ANS function between healthy people and CHF patients by calculating the high / low frequency ratio (LH) between experimental samples. It can be seen from Figure 1 that the LH index of CHF patients is significantly lower than that of healthy control group, demonstrating that chronic heart failure will lead to ANS dysfunction.

The IBS index of CHF patients is lower than that of healthy people, indicating that there is a certain similarity between continuous heartbeat, but the similarity between adjacent RRs of CHF patients is lower. To some extent, it reflects that bradycardia or tachycardia may cause this phenomenon when chronic heart failure occurs. At the same time, we can infer that the information similarity will increase with the aggravation of the disease. The more times and longer time of failure caused by severe patients may be an important reason for this phenomenon.

4.3 Parameter selection

Sympathetic and parasympathetic nerve stimulation can affect autonomic nerve function at the same time [15], and then affect the heart rate. Therefore, in the calculation of information similarity, using 0 and 1 to represent the rise and fall of RR interval respectively and converting RR sequence into binary sequence can more clearly eliminate the influence of inherent noise in autonomic nervous system, and directly reflect the activities of sympathetic and parasympathetic nerves.

In order to reflect different dynamic wave patterns more clearly, binary sequences are transformed into alphabetic sequences composed of binary numbers of different lengths. Just as different writers have different preferences and habits of using words, the number and frequency of different letters can also reflect the important physiological information of each unique individual. By calculating the information similarity index IBS, the similarity between two symbol sequences can be measured. Therefore, using IBS index to measure the alphabetic sequences transformed from adjacent RR sequences can quantify this association and further analyze the underlying dynamic mechanism of CHF, which provides a new perspective for the study of CHF diseases.

In the process of transforming binary sequence into alphabetic sequence, we calculate the IBS index when the length parameter m is 2-8. As shown in Figure 2, for one minute RR sequence samples, when the length parameter $m = 6$, the combination of sibs and HFR has the best screening performance. Therefore, we will choose $M = 6$ for follow-up study.

4.4 Limitations of our work

In this experiment, we strive to make the results scientific and reliable, but it is inevitable that there are still factors to be improved and strengthened.

First of all, restricted by the experimental equipment, we can only choose systematic and reliable existing database for research and analysis rather than collect data independently. That leads to the limited number of our samples, only 98 in total, and the quality of the samples is uneven, and there is a big difference in age and gender.

More detailed research will greatly reduce the reliability of the data, so this experiment did not consider the influence of age, gender and other factors. There is still space to adjust the underlying architecture of the algorithm to make it more suitable for our research and more efficient. In the future research, we can follow up and improve some of the above problems. And we are going to share our latest research results in the future.

5. Conclusion

In the course of this experiment, we mainly analyze the symptoms of chronic heart failure. Starting from the heart rate information, we analyze the effect of high-low frequency ratio and information similarity index, and improve and synthesize them. We give the theoretical results of our joint judgment by combining information similarity and high-low frequency ratio.

Through the comprehensive analysis of the two, we can identify the symptoms of chronic heart failure through daily heart rate monitoring data with 87.8% accuracy, and our method has excellent discriminant significance ($P < 0.01$).

Our research provides a good auxiliary diagnosis and treatment method for chronic heart failure, which is characterized by small early and mild symptoms, slow onset, difficult to diagnose and serious harm. Our research has rich data collection, high accuracy, low misjudgment rate, simple equipment, and does not affect the daily life and physical and mental health of the wearer, It has the characteristics of technical background support of professional hospital, which provides good early theoretical support and data processing experience for the monitoring and early warning of chronic heart failure symptoms in the future.

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