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Chenjun She, Xiefeng Cheng, and Jing Wang

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Chenjun She, Xiefeng Cheng, and Jing Wang

AFFILIATIONS
Electronic Science & Engineering, Nanjing University of Posts and Telecommunications, 210023 Nanjing, China

ABSTRACT
Heart sound is a kind of non-stationary and nonlinear signal with typical chaotic characteristics. As everyone knows, exercise and age can influence heart function, will they also influence the chaotic characteristics of heart sound? This problem is studied based on the correlation dimension and Kolmogorov entropy. Firstly, discuss calculation methods of correlation dimension and K entropy of heart sound signal. Secondly, introduce the experimental methods, and use a self-made wireless heart sound acquisition device to collect heart sound signals in different move status and at different ages. The effects of exercise on correlation dimension and K entropy were discussed in three status of rest, in and after exercise. Then carry out phase plane analysis of heart sound signals, and analyze change rules of correlation dimension of heart sound signals with aging. Finally, the prediction model of heart sound is proposed according to the relationship between age and correlation dimension. The results show that: (1) There were significant differences in correlation dimension and K entropy of heart sound signals under different move status. (2) Affected by cardiac inefficiency and pathological murmurs, correlation dimensions of heart sound decrease with the increases of age. Therefore, senescence is a process in which the chaotic characteristics of heart sounds gradually change to zero. (3) According to the prediction model of heart sounds, we can try to obtain heart sounds for many years to come, which can be used to assist in predicting the risk of human-related diseases in a certain sense.

I. INTRODUCTION

Chaos refers to irregular behavior that appears to be random but is not. Chaos is ubiquitous in nature, economy and human society, especially in nonlinear biological systems. In recent years, with the deepening of research, it has been found that many chaotic systems, especially life systems, show chaotic characteristics. And chaotic systems become a difficulty and hotspot in the study of chaos. The heart is a complex nonlinear dynamic system, which determines that heart sound signals generated by it also have nonlinear and complexity. The normal and abnormal heart sounds are analyzed by using the maximum Lyapunov exponent, fractal dimension, complexity, K entropy, correlation dimension, and other chaotic parameters, and it is found that these parameters have different meanings.

Experimental and numerical results show that the traditional linear analysis method is not enough to show the nature of nonlinear motion. Chaotic motion is a very important movement mode in the nonlinear system, and chaos phenomenon appears in various chemical, physical and biological systems. The structure of the heart is self-similar or fractal in many aspects, and the heart is capable of chaotic behavior, which is characterized by chaos. Since the heart needs the exchange of energy and matter, it can be considered that the heart is a chaotic dissipative system. Based on chaos theory, this paper carried on the analysis of heart rate that traffic noise increases the heart rate variability HRV complexity. The metabolic and cardiac rhythm changes were analyzed by chaos theory. The algorithm based on the phase space reconstruction method analyzes the RR sequence of ECG and classify Atrial Fibrillation (AF), and the proposed algorithm tied for the first place in the PhysioNet/CinC Challenge 2017 with an overall score of 82.6%. Introduction of the methods commonly used in nonlinear research of cardiac electrical signals and the parameters commonly used in chaos theory is made. In the study of the chaos of ECG signals, the electrical signals of cardiac myocytes after excitation show deterministic chaos. Heart sound and ECG are acoustic and electrical manifestations of
heart motion characteristics. Heart sound originates from the heart and has fractal characteristics, so it has the chaotic characteristics related to the heart. Therefore, the analysis and research based on chaos theory can better reveal the inherent special rules of heart sound about chaos. The Lyapunov index and correlation dimension were used to analyze and calculate the normal and arrhythmia heart sound signals. It was proposed that the correlation dimension and maximum Lyapunov could be used to analyze arrhythmia signals and extract their characteristics. The chaotic characteristics of heart sound signal are studied by the maximum Lyapunov index analysis, and the paper seeks a non- adaptive and intuitive way to differentiate the normal and abnormal heart sound signals to provide more valuable reference method for the clinical diagnosis. Extract the features of heart sounds and classify them by analyzing the chaotic characteristics of wavelet packets, and the results show that the recognition rate of Ref. 9 is higher than the traditional classification method, which shows that the nonlinear chaotic feature can effectively represent the heart sound signal. Based on the chaotic characteristics of heart sound, a chaotic inverse control method of heart sound is proposed to regulate the functional status of the heart through in vitro control. The signal nonlinearity and statistical analysis are used to preprocess feature extraction and classification of heart sounds. The PhysioNet/Computing in Cardiology Challenge 2016 (www.physionet.org/challenge/2016), aims to encourage the development of algorithms to classify heart sound recordings collected from a variety of clinical or nonclinical (such as in-home visits) environments. This provides a platform for our extensive study of heart sounds. Gari D. Clifford considered that the Challenge provided a state-of-the-art open-source heart sound segmentation algorithm for this Challenge, which is an excellent work, and they would intend to work with industry and researchers alike to enhance the Challenge database in all these areas. Qurat-ul-Ain Mubarak proposed a system for heart sound localization and classification base on “Pascal Classifying Heart Sound Challenge”.

Age is an independent risk factor for cardiovascular disease. As for the influence of age on HRV, foreign researchers have done a lot of research and made abundant achievements. In February 2020, Goldberger et al. in a review of PNAS, pointed out that the influence of age on autonomic nerve function is mainly reflected in cardiac autonomic balance were assessed in master athletes and compared with age-matched controls and young untrained controls. Meanwhile, the influence of age on autonomic function nerve is mainly reflected in the vagus nerve. The effects of lifelong endurance and sprint training on cardiac autonomic balance were assessed in master athletes and compared with age-matched controls and young untrained controls. Or master athletes, regardless of whether they are trained in endurance or sprinters, both training modes revealed to be equally beneficial in attenuating the effects of aging on the autonomic balance. To sum up, heart sounds are chaotic. Do exercise and age have any effect on the chaotic nature of heart sounds? There were no immediate reports. Therefore, we designed a set of experimental methods, using the self-made wireless heart sound acquisition device, to collect the heart sound signals under the move status and at different ages. Based on the correlation dimension and K entropy of heart sound, we study the effects of exercise and age on the chaos of heart sound. Firstly, we compare the correlation dimension and K entropy of heart sounds in different move status. Through the exercise load experiment, a method commonly used in this study to induce potential cardiovascular diseases, it was found that with the progress of exercise, the adaptive ability of the heart would change, and after exercise, the chaotic characteristics of heart sound would be enhanced. Secondly, we compare the correlation dimension of heart sounds in different ages, and the influence rule of age on the chaotic characteristics of heart sound was analyzed. It is proposed that the aging process is a process in which the chaotic characteristics of heart sound gradually change to zero. Finally, according to the correlation dimension of heart sounds, we propose a prediction model of heart sounds. The results show that the correlation dimension and K entropy can be used as the quantitative evaluation indexes of the chaotic characteristics of the heart sound.

II. CHARACTERIZATION METHODS OF CHAOTIC CHARACTERISTICS OF HEART SOUND

A. Phase space reconstruction of heart sound

Phase space reconstruction is an important method to extract information of chaotic characteristics of heart sound, and it’s also the first step to analyze the size of correlation dimensions. According to Takens theorem, if \( X(t), t = 1, 2, \ldots, N \) represents the observed sequence of heart sound, selecting appropriate delay and embedding dimension to reconstruct phase space, and a new group of vector sequence is obtained from \( x(t) \):

\[
X(t) = \{x(t), x(t + \tau), \ldots, x[t + (m - 1)\tau]\}^T
\]

Where \( t = 1, 2 \ldots M, M = N - (m - 1)\tau, \tau \) is delay time. Then the M-dimensional state space of phase space is reconstruction, which is constituted by the value of heart sound observation and delay, and it is diffeomorphism with the original state space.

B. GP algorithm to quickly solve correlation dimension

The Correlation dimension is a quantitative index to measure the complexity of phase space attractor of chaotic time series. After phase-space of heart sound was reconstructed, we can extract correlation dimensions, which is a quantitative indicator measuring phase space attractor complexity of chaotic time series. According to the physical characteristic of heart sound and Takens embedding theorem, in this paper, it uses the GP method to rapidly calculate chaotic characters of the heart sound.

After phase space reconstruction of heart sound for M points, calculating its associated vector pairs, its proportion in all possible pairs in \( M^2 \) is called correlation integral.

\[
C_n(r) = \frac{1}{M^2} \sum_{i,j=1}^{M} \theta[r - \|X(i) - X(j)\|]
\]

Among them, \( \theta(\cdot) \) is a Heaviside unit function

\[
\theta(x) = \begin{cases} 
0, & x < 0 \\
1, & x > 0 
\end{cases}
\]
When \( r \to 0 \), the relation of \( C_n(r) \) with \( r \) is \( \lim_{r \to 0} C_n(r) \propto r^D \), among them, \( D \) is correlation dimensions. Appropriately to chose \( r \), \( D \) can describe the self-similar structure of strange attractor. By the above relation, we can get \( D = \log C_n(r)/\log r \). In normal numerical calculation, the usual practice is to increase the embedding dimension from small to large. Taking straight segment part of the double logarithmic relationship \( \log C_n(r) \sim \log r \) for each embedding dimension, an optimum straight line is obtained, with using least-squares fitting. The slope of it is called the correlation index, which will increase with the increasing of embedding dimension. Finally, it will reach saturation values, which are correlation dimensions of chaotic time series of the heart sound.

C. GP algorithm to quickly solve correlation dimension

In the phase space of the heart sound signal \( X(t) = [x(t), x(t+T), \ldots, x(t+(m-1)T)]^T \), the assumption is that \( m \)-dimensional phase space was divided into boxes of size \( a \). The phase space is divided into \( L \times a \) symbol space. Sampling the state of the system at certain intervals, if \( k \)th time state point \( X(k) \) fall in the \( j \)th symbol interval, define the symbol \( s(k) = j \), \( j \in \{1, \ldots, L\} \), then the delayed heart sound starting from time 0 can be completely described by the symbol vector \( S = [s(0), s(1), \ldots, s(n-1)] \) with length \( n \). Let \( N(n) \) be the number of symbol vectors of length \( n \). Let \( P_i \) be the probability of the \( i \)th symbol vector of length \( n \).

\[
P_i = P\{s_i(0) = j_0, s_i(1) = j_1, \ldots, s_i(n-1) = j_{n-1}\} \quad (4)
\]

Entropy \( K \) can effectively judge the nature of the signal. \( K = 0 \) representing regular motion, \( K \to \infty \) representing random motion and \( 0 < K < \infty \) representing chaotic motion. For one-dimensional regular motion, initially adjacent points stay adjacent, we can get \( P_{i0} = L, P_{i0i1} = L \times 1, K = 0 \). For one-dimensional random motion, initially adjacent points are distributed with equal probability over all newly allowed intervals, we can get \( P_{i0} = L, P_{i0i1} \propto L^2, K \propto -\log L \to \infty \). For one-dimensional chaotic motion, initially adjacent points become exponentially separated \( P_{i0} = L, P_{i0i1} = L e^{-\lambda}, K = \lambda > 0 \). Here we assumed for simplicity that a) \( P_{i0i1} \) factorizes into \( P_{i0} \cdot (1/N) \) where \( N \) is the number of possible new intervals which evolve from \( i0 \) and b) \( K_{n+1} - K_n = K_1 - K_0 \) for all \( n \).

FIG. 1. Chaotic characteristic parameters \( D \) and \( K \) of heart sound, (a) heart sound waveform (b) correlation dimension \( (D) \) - embedding dimension \( (m) \) (c) \( K \) entropy(K) - embedding dimension \( (m) \).
D. Calculation of chaotic characteristic parameters of heart sound

Taking the heart sound signal data of 12000 points shown in Fig. 1(a) as an example, the correlation dimension and K entropy of signals with the increasing of embedding dimension can be obtained according to Eq. (2) and Eq. (5). It can be seen from Fig. 1(b) that the correlation dimension of heart sounds tends to be stable with the change of the embedding dimension. Fig. 1(c) shows the change of the K entropy with the embedding dimension, K entropy greater than 0 indicates that heart sounds are chaotic, which is consistent with previous studies.

III. EXPERIMENTAL METHODS

In this paper, we collected the heart sound signals by the self-made wireless shoulder-wearable heart sound acquisition device (The patent number is ZL201310454575.6), as is shown in Fig. 2(d). The device consists of lightweight elastic materials to form a Ω frame component, and its shape similar to outside contour lines of the human body shoulder to the chest, which makes the framework can be easily placed in the left shoulder. The device can be attached to the wearer’s chest for real-time collection of the heart sound. And then through a wireless transmission module, the signal is transmitted to the PC for reprocessing and analysis. This type of device provides strong support for the collection of heart sound signals in exercise.

Basic technical indicators of the self-made shoulder-wearable heart sound-acquisition device: wireless carrier frequency 2400MHz; Built-in lithium battery, working current and voltage: 60mA, DC5.0v; Frequency response 20hz-2khz; SNR 90Db; Distortion <1%; Sampling rate: 16bit, 48KHz; Receiving range and distance R=50m; Adjustable magnification; Operating temperature:-10°C to 60°C; Continuous working time: about 6 hours.

Two experimental methods are designed in this paper. The first method is to collect heart sound signals according to different age groups. The population is divided into three age groups: Young group, Middle age group, and Old age group, included both men and women: (1) Age ranging from 10 to 28 years called Young group and the number of subjects is 9. (2) Age of 8 subjects ranging from 35 to 60 years called Middle age group. (3) Age ranging from 61 to 80 years called the Old age group and the number of subjects is 5. All the subjects were in sinus rhythm, with no history of cardiovascular disease and the subjects are quiet breathing in the resting state for continuous signals collection about two minutes. Heart sounds collected by people of different ages are respectively shown in Figure 2(a), (b) and (c).

The second method is to collect heart sound signals according to different move status, at rest, in exercise and after exercise. Ten healthy men with an average age of 25.2 were selected and numbered 1-10 respectively. Collecting heart sound signals of ten healthy men with an average age of 25.2 years, at rest, in exercise (constant speed bicycle training lasts for 5 minutes) and after exercise respectively. That is a total of 30 cases of heart sounds. In the experiment, the support of the sound-collecting device should be firmly wrapped in the left shoulder of the tester, and the heart sound sensor should be pressed to the central position of the human heart to reduce the error of heart sound data caused by human factors. Ensure that the sensor position and pressure applied to the sensor are as stable as possible in all tests, and inform the tester to avoid large movements of the upper body as far as possible, so as not to affect the reliability of the experimental data. Finally, the biorthogonal wavelet of heart sound is used to denoise and preprocess all heart sound signals.

IV. EFFECTS OF MOVE STATUS AND AGE ON CORRELATION DIMENSION AND K ENTROPY OF HEART SOUNDS

A. Effect of different move status on correlation dimension and K entropy of heart sound

The chaotic characteristics of 30 cardiac sound signals from 10 people at rest, in exercise and after exercise recovery were
analyzed. GP method is adopted to calculate the correlation dimension of heart sound signal according to Eq. (2), and K entropy of the heart sound signal is obtained according to Eq. (5). As shown in Fig. 3(a), a concrete example from tester numbered 1 is provided, which shows that his correlation dimensions of heart sound change along with embedding dimension at rest, in exercise and after exercise. When embedding dimension \( m > 16 \), the curve tends to be flat. The correlation dimensions are calculated respectively when \( m = 16, 18 \) and 20, and let average of them to be the correlation dimension of heart sound (\( D \) is correlation dimension; \( m \) is embedding dimension). Fig. 3(b) shows the change of heart sound K entropy with the embedded dimension in the three states of the same test object. K entropy is an important measure of chaotic motion in the phase plane, which is proportional to the rate of state information loss of the dynamic system. The K entropy of the same test object in different states is obviously different, which can be used to distinguish the move status of the test object. It can be used as a feature for the classification of move status.

Chaotic feature analysis was carried out on all 30 heart sound signals of 10 people at rest, in exercise and after exercise recovery. The results are shown in Table I.

(a) As can be seen in Table I and Fig. 3(a), with the increase of embedding dimension, the average correlation dimension of heart sound tended to change regularly in three states: resting, moving and recovering.

(b) It can be seen from Table I and Fig. 3(b) that the K entropy in the resting state is large, while that in the motion state is small.

(c) By comparing Fig. 3(a) and (b), there is a direct proportional correspondence between K entropy and correlation dimension in the three states, both of which are larger in the resting state. Because K entropy reflects the average rate of information loss. When the correlation dimension is large, the heart sound has stronger chaotic, its convergence or divergence will be faster, and the average rate of information loss will be faster, so the K entropy will be larger. The range of K entropy is much higher than the correlation dimension.

Further quantitative analysis is shown in Figure 4. Fig. 4 shows:

(a) That correlation dimensions in exercise became smaller than before, decline ratio is 12.3% - 53.8%. In the process of

![FIG. 3. Tester’s chaotic characteristic of heart sound with embedding dimension changing, at rest, in exercise and after exercise. (a) The relationship between correlation dimension and embedding dimension in three states, (b) The relation between K entropy and embedded dimension in three states.](image)

### Table I. Mean of Correlation dimension and measure entropy K of testers in different states of exercise.

| embedding dimension | 2   | 4   | 6   | 8   | 10  | 12  | 14  | 16  | 18  | 20  |
|---------------------|-----|-----|-----|-----|-----|-----|-----|-----|-----|-----|
| Correlation dimension of testers | Rest | 0.39| 1.48| 2.11| 2.47| 3.05| 3.43| 3.74| 4.28| 4.37| 4.42|
|                      | In  | 0.14| 0.37| 0.78| 0.95| 1.13| 1.28| 1.53| 1.85| 2.14| 2.26|
|                      | After| 0.22| 1.15| 1.52| 2.07| 2.23| 2.56| 2.87| 3.39| 3.52| 3.67|
| measure entropy K of testers | Rest | 32.78| 33.47| 34.33| 37.08| 40.13| 43.24| 48.34| 42.59| 38.55| — |
|                      | In  | 11.12| 12.16| 13.53| 15.23| 17.41| 19.12| 20.32| 17.27| 14.93| — |
|                      | After| 24.16| 25.11| 27.64| 29.07| 33.92| 27.4 | 29.52| 28.83| 26.98| — |
exercise, the heart rate is accelerated, the sympathetic part of the autonomic nerve becomes excited, and the vagus part is inhibited. This change destroys the balance of the autonomic nerve of the human body, and weakens the heart rate variability, and then simulates the state that the heart is affected by diseases. This leads to a decrease in the ability of the cardiovascular system to regulate heart regulation, which reduces the chaotic nature of the heart, and in turn, leads to a decrease in the number of heart sound correlation dimensions.

(b) Meanwhile, correlation dimensions began to rise in the recovery phase of 3 minutes, the rising ratio is 7.8%~48.5%. This is because after exercise the recovery phase is a long process and the heart rate needs to gradually decrease. The continuous regulation makes the heart reach a new balance between the sympathetic nerve and the vagus nerve. In this process, factors influencing the cardiovascular changes will increase, and the regulation process will become complex, and the chaotic nature of the cardiovascular system will be strengthened again.

(c) According to the survey, the sportsman (number 7) in the test group had the highest correlation dimension of heart sound at rest. And K entropy is also the highest because it is related to the correlation dimension. The variation range of the correlation dimension of heart sound in exercise and after exercise was relatively small. Therefore, exercise enhanced the chaotic characteristic of heart sound, and the chaotic characteristic parameters of heart sounds tend to be relatively stable.

The most visual way to observe the dynamic behavior of a chaotic system is through the phase plane, which is the track record of the chaotic system and can reflect the changes of the system state. For the convenience of observation, a phase plane is often studied to directly judge the nonlinear dynamic behavior of chaotic systems. For example, for periodic motion, the phase diagram trajectory is a simple closed curve. Because heart sound is a quasi-periodic signal, we further use the phase plane to analyze the chaotic characteristics of the heart sound.

Fig. 5(a) is the heart sound waveform, attractor phase diagram and correlation integral distribution diagram of the resting state of test object 1 before exercise. Fig. 5(b) shows the heart sound waveform, attractor phase diagram and correlation integral distribution diagram in the exercise. Fig. 5(c) shows the heart sound waveform, attractor phase diagram and correlation integral distribution diagram after exercise. Three kinds of statuses are depicted as correlation integral distribution curve $\ln C_m(r) = \ln r$ respectively. The embedding dimension from an initial 2 gradually increase to 20, the interval $\Delta m = 2$. We can utilize least-squares fitting method to determine scale region, that is the linear-related part between $\ln C_m(r)$ and $\ln r$ in saturation region. Then let the fitting slope to be the correlation dimension of the heart sound. If chaotic characteristics exist in the system, the embedding dimension increase and correlation dimension will also increase. But, when $m$ increases to a certain extent, the correlation dimension will gradually present convergence.

The phase plane is mainly composed of fixed point and closed orbits. The attractor phase plane of three states of heart sound signals in Fig. 5 shows that closed orbits in the phase plane across each other, and the phase plane has an obvious area. Nearby orbits are drawn into this bounded region, by K entropy value greater than 0 at the same time, the attractor in phase plane form a strange attractor. Moreover, the attractor phase plane of heart sounds in different states has significant differences in the complexity of track distribution and the size of the distribution region. The phase space attractor distribution area of the heart sound signal in exercise is obviously larger than at rest and recovery stage, and the trajectory ordering is poor. The tracks of the reconstructed phase plane of rest and after exercise states are obviously sparse than those in exercise. It indicates that the chaotic complexity of heart sound signals decreases firstly and then increases on the whole due to the autonomic regulation of the heart in the process from rest to recovering after exercise. This further indicates that exercise has an effect on the chaotic characteristics of the heart sound.

B. Effect of different age on correlation dimension of heart sound

Correlation dimensions of chaotic characteristic are analyzed by means of collecting the heart sound of different age groups, with the calculation of correlation dimensions of heart sounds of 22 cases. And use linear fitting by the graphing method to find the trend of correlation dimensions with the age increasing. Fig. 6 shows correlation dimensions of heart sound trending with age changes. (D is correlation dimensions, Y is age.)

From Fig. 6, correlation dimensions of heart sound have a remarkably negative linear relationship with age, and the P-value of the linear regression equation is less than 0.01, which has a statistical meaning. With age increasing, correlation dimensions of heart sound overall presented a decreasing trend. Through linear fitting of experimental data, prediction equation of correlation dimensions of
heart sound changed with age is

\[ Y = 4.51977 - 0.0398 \times X \]  

(6)

When \( Y = 0 \), then \( X = 113.5621 \). That is, the correlation dimension of heart sound tends to 0 at 113 years old, correlation dimensions of heart sound annual reduces average 0.0398%, and chaotic characteristics of heart sound will disappear completely. This also provides a new prediction method of human life.

From the perspective of human physiology, with aging, the vagus nerve will degenerate, the regulation of myocardial function
will weaken, which makes myocardial systolic function decline, at the same time, the adaptive capacity of the heart also decreased. This leads to the decrease of the state variables of the heart system, namely the information contained in the heart sound time series, which leads to the decrease of the correlation dimension of the heart sound.

The nonlinear chaotic characteristics of the heart sound of Young people and Middle-aged people presented higher values. This indicates that at this age level, the amplitude of the heart sound signal is relatively strong, and there are many factors affecting the cardiovascular changes, the regulation process is relatively complex, and the heart system presents a stronger chaotic state, thus complicating the cardiovascular nonlinear dynamics system. However, in the old aged people, the cardiovascular system has decreased cardiac regulation ability, leading to the decreased intensity of the heart sound signal. At the same time, under the influence of abnormal pathological cardiac murmur, the chaotic characteristics of the cardiovascular system are weakened and tend to be orderly movement. Therefore, senescence is a process in which the chaotic characteristics of cardiac tone are attenuated to zero.

V. APPLICATION BASED ON CORRELATION DIMENSION OF HEART SOUND: A HEART SOUND FORECASTING MODEL

A. Forecasting model

A heart sound forecasting model will play an important role in the diagnosis of heart disease. Based on previous studies, abnormal heart sound often has murmurs along with the changing of age and physical constitution, and according to Eq. (6) and the linear expression of heart sound in the time domain, we present a forecast model for heart sound, as shown in Fig. 7.

Heart sound signal forecast model is shown in Eq. (7):

\[
S_D(Y) = S(t) - \Delta e^\alpha Y S_R(t) \tag{7}
\]

Where \(\Delta e^\alpha Y\) is a nonlinear composite term, \(\Delta\) represents the attenuation of amplitude per year, \(\alpha\) is attenuation composite coefficient, \(Y\) is the length of the forecast period. \(S_R(t)\) is a mixture of chaotic characteristic attenuation \(S_C(t)\) and current heart signal \(S(t)\).

According to experimental statistics and research literature over recent years, the heart sound amplitude of healthy people began to appear obvious decline in about 55–70 years old and the decay rate is about 0.04–1.8% annually. However, for those suffering from heart disease in ages, the amplitude of heart sound shows more rapid attenuation, and the decay rate is about 1.5~10% annually. Combined with experimental data, we provide the evaluation criteria of attenuation coefficient \(\alpha\), as shown in Table II.

Chotic characteristic attenuation of heart sound \(S_C(t)\) is determined as follows: (1) Set up a database of heart sound signal corresponding to different correlation dimension (D value) range from 0.3 to 4.5. (2) Calculate the D value of the current heart sound signal. Predict the future DL according to the average annual attenuation of D value. (3) Select the heart sound signal as chaotic characteristic attenuation component of heart sound \(S_C(t)\) from the database corresponding DL, and the time of signals in database are the same.

The current heart sound signal \(S(t)\), can be regarded as periodic signal and expressed as:

\[
S(t) = C_1S_1 + C_2S_2 + C_3S_3 + C_4S_4 \tag{8}
\]

Where \(S_1\), \(S_2\), \(S_3\), \(S_4\) are the first second, third and fourth heart sound. \(c_n (n=1, 2, 3, 4)\) are synthesis coefficients. Because of the weakness of \(S_3\) and \(S_4\), we can omit them in the studies.

The layering and mixing method of \(S_C(t)\) and \(S(t)\) is as follows: (1) Extract the first heart sound \(S_1\) and the second heart sound \(S_2\) of them respectively in one cycle. (2) The layer above four signals with equal length by \(N\)th WPT transform, we can obtain a low-frequency part and \(N\) high-frequency parts \(I_{j}^L, j = 1, 2, \ldots, N\). (3) All the narrowband signals decomposed in \(S_C(t)\) and \(S(t)\) are weighted average:

\[
I_{j}^L = \frac{1}{T} \sum_{i=1}^{T} \beta_1 I_{i}^L \tag{9}
\]

\[
I_{j}^H = \frac{1}{T} \sum_{i=1}^{T} \beta_2 I_{i}^H, (j = 1, \ldots, N)
\]

| influence factor | Attenuation coefficient |
|------------------|-------------------------|
| constitutional index (BMI): Too thin or fat | +0.2 |
| Family history: coronary heart disease, diabetes and hypertension | +0.2 |
| Unhealthy living habit (Cigarettes, alcohol, less exercise...) | +0.1 |

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A. Conclusion 1

The chaotic characteristics of heart sound changes with different move status. The experimental results show that from rest into exercise, the correlation dimension of heart sound decreased by 12.3% ~ 53.8%, and the value of K entropy is also small. After exercise, it increased by 7.8%~48.5%, and the value of K entropy goes up. Therefore, exercise can enhance chaotic characteristics of the heart sound. Keeping exercising, then chaotic characteristics of heart sound will tend to be stable, so proper sports activities keep our physical fitness.

B. Conclusion 2

Aging is the process that the chaotic characteristic of heart sound gradually decays to zero. The experimental results show that aging will lead to the weak chaotic characteristic of the cardiovascular system, correlation dimension of heart sound approximately reduced by 0.0398% per year.

C. Conclusion 3

Based on the correlation dimension of heart sound, we proposed a prediction model of the heart sound. We can try to get heart sounds data after many years. The prediction data can be applied to the classification of heart sounds, which can be used to assist in predicting the risk of human-related diseases in a certain sense.

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REFERENCES

1. M. A. Quiroz-Juárez, R. Vázquez-Medina, E. Ryzhii, M. Ryzhii, and J. L. Aragón, “Quasiperiodicity route to chaos in cardiac conduction model,” Communications in Nonlinear Science and Numerical Simulation 42, 370–378 (2017).
2. M. Alves, D. M. Garner, M. Anne, G. G. Fontes et al., “Linear and complex measures of heart rate variability in exposure to traffic noise in healthy women,” Complexity 2018, 1–14.
3. J. Weiss, A. Garfinkel, M. L. Spano, and W. L. Ditto, “Chaos and chaos control in biology,” Journal of Clinical Investigation 93(4), 1355–1360 (1994).
4. M. Zabihi, A. Bahrami Rad, A. K. Katsaggelos et al., “Detection of atrial fibrillation in ECG hand-held devices using a random forest classifier,” 44th Computing in Cardiology Conference (CinC), Computing in Cardiology (2017).
5. X. Ning, C. Bian, and J. Wang, “Research progress in nonlinear analysis of heart electric activities,” Chinese Science Bulletin 51(4), 385–393 (2006).
6. H. G. Schuster and W. Just, “Deterministic chaos: An introduction, 4th, revised and enlarged edition,” Quarterly Review of Biology (2005).
7. X. R. Ding, X. M. Guo, L. S. Zhong, and S. Z. Xiao, “Analysis of the heart sound with arrhythmia based on nonlinear chaos theory,” Journal of Biomedical Engineering 05, 810–813 (2012).
8. L. Sun, L. Sun, and X. Peng, “Chaotic characteristics of heart sound signals based on the largest Lyapunov exponent,” Applied Mechanics and Materials 411–414, 1117–1124 (2013).
9. X. Guo, X. Ding, L. Zhong et al., “Heart sound feature extraction and classification based on integration of wavelet packet analysis and chaos theory,” Chinese Journal of Scientific Instrument 33, 1938–1944 (2012).

10. X. Cheng, C. She, and J. Li, “Anti-control method of heart sound based on its chaotic characteristics,” Journal of Vibration and Shock 37, 178–184 (2018).

11. C. Xie-feng, J. Bin, Y. He, G. Yu Feng, and Z. ShaoRui, “A new method of heart sound signal analysis based on independent function element,” AIP Advances 4(9), 097131 (2014).

12. X. Cheng and Z. Zhang, “Denoising method of heart sound signals based on self-construct heart sound wavelet,” AIP Advances 4(8), 087108 (2014).

13. C. Liu, D. Springer, and G. D. Clifford, “Performance of an open-source heart sound segmentation algorithm on eight independent databases,” Physiological Measurement 38, 1730–1745 (2017).

14. G. D. Clifford et al., “Recent advances in heart sound analysis,” Physiological Measurement 38(8), E10 (2017).

15. Q.-u.-A. Mubarak, M. U. Akram, A. Shaukat et al., “Analysis of PCG signals using quality assessment and homomorphic filters for localization and classification of heart sounds,” Computer Methods and Programs in Biomedicine 164, 143 (2018).

16. J. Wu et al., “The role of oxidative stress and inflammation in cardiovascular aging,” BioMed Research International 2014, 1–13.

17. A. L. Goldberger, L. A. Amaral, J. M. Hausdorff, P. C. Ivanov, C. K. Peng, and H. E. Stanley, “Fractal dynamics in physiology: Alterations with disease and aging,” Proceedings of the National Academy of Sciences 99, 2466–2472 (2002).

18. L. Alves Deus, C. Victor Sousa, T. Santos Rosa et al., “Heart rate variability in middle-aged sprint and endurance athletes,” Physiology & Behavior 205, 39–43 (2019).

19. L. V. Jinhu, L. U. Junan, and S. Chen, Chaos time series analysis and its applications (Wuhan University Press, Wuhan, 2002).

20. Y. Zeng, Study on cardiovascular risk assessment and comprehensive intervention in older adults (Central South University, Changsha, 2012).

21. X. Ceng, Y. Li, W. Jiang, Z. Yan, and C. She, “Heart sound prediction model, method and application based on chaos theory,” Journal of Nanjing University of Posts and Telecommunications (Natural Science Edition) 36(03), 33–39 (2016).