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Feature extraction of pulse wave signal[1]

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Abstract. Nowadays cardiovascular disease has become "the number one killer" of human life and health. Most of the clinical diagnosis is invasive means, in which the patients have pain without real-time monitoring. Aiming at the problems of pulse wave in the diagnosis of cardiovascular diseases, the method of pulse wave time domain and frequency domain analysis was used in this paper. The parameters related to coronary heart disease were found out from the characteristic parameters by the feature recognition technology, which were used to establish the identification model. And the simple parameter report was associated with the disease diagnosis. For the first time, the complex parameter–wavelet entropy analysis method was introduced into the field of pulse wave feature detection.

Key words. Pulse wave, wavelet transform, fuzzy recognition.

1. Introduction

The vascular system of the human body is a whole body composed of heart, blood vessels and blood. Under the condition of mutual coordination and restriction and the control of the central nervous system, the whole process of blood circulation is completed. The pulse signal is generated by the heart beat to push blood along the blood vessels. Therefore, according to the modern scientific viewpoint, the pulse signal can be regarded as the output and mapping of the internal motion of the heart in the human body (Wang et al. 2002) [1]. The pulse wave is mainly formed by the contraction and relaxation of the heart and the interaction of various resistances along the blood vessels. So when the pulse wave spreads from the heart to the arterial system, it is not only affected by the heart itself, but also affected by various physiological factors, such as vascular resistance and blood vessel wall

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elasticity. Therefore, the pulse wave signal contains a great deal of physiological and pathological information of cardiovascular system. The waveform characteristics and harmonic information of pulse wave are closely related to the change of characteristic parameters in the cardiovascular system (Qiao et al. 2000) [2]. There is a close relationship between traditional Chinese medicine pulse and Waveform shape of pulse wave. Over the years, researchers have made great achievements in the non-invasive diagnosis of cardiovascular diseases by exploiting the relationship between physiological parameters such as pulse wave parameters and pathology, and summarized a large number of parameters related to cardiovascular disease in time domain and frequency domain. However, there are a large number of parameters, and an effective evaluation criteria is needed for which parameters are more relevant to cardiovascular pathology (Mollet et al. 2005) [3]. It is difficult to understand the relation between the single parameter and the physiological information with poor systematicness, which can only provide single index evaluation and no disease diagnosis. All these problems make the application of research results in hospital clinic and patients' daily health care subject to a certain degree of limitation (Yang et al. 2002) [4]. In addition, the research on the characteristic parameters of pulse wave in time and frequency domain is very large, so it is necessary to develop new research ideas (Wang et al. 2001) [5].

2. State of the art

In 1775, the famous Swiss mathematician Euler studied quantitatively the law of pulse wave propagation in human body for the first time. Since then, it has been one of the most important problems in the field of biomechanics and biomedicine to detect the information of human pulse system and establish the dynamic model of human cardiovascular system [6–8]. For the first time, Erasistratos found that the pulse was a kind of wave propagation. However, because of the lack of the concept of blood circulation, it was also very superficial understanding of the pulse. He believed that the blood from the heart contracts pushed forward the blood column in the blood vessel, which was the periodic expansion of the blood vessels and the "driving" theory. Until the beginning of seventeenth century, British physician Harvey first discovered and recognized the phenomenon of blood circulation. In 1775, Leonard Eular first gave the governing equations describing the flow of incompressible ideal fluid in an elastic tube. Since then, people had been really starting to develop a correct description of the pulse system. Thomas Young, Ernst Heinrich Weber, Korteweg, Lamb, Witzig and others had improved and obtained different pulse wave velocity formula in different cases. In 1898, Otto Frank proposed a quantitative model of the artery as an elastic cavity. The elastic cavity model gave a better approximation of the pressure and flow waves in the large arteries. The modern analysis of pulse wave propagation began in 1950s. During 1950s to 1970s, the most representative researchers included Womersley, Mc Donald, Bergel, Fung and Gang Xiaotian. They established a linearized model of the pulse wave in the arterial segment, developed the Windkessel model and discussed he law of pulsatile flow on the basis of this. Cox et al. extended the thin wall model used by Womersley to the case of finite thickness wall, which made the results more likely to correspond to the actual arterial wall [9–11].

3. Methodology

3.1. The relationship between pulse wave and cardiovascular disease

The resistance to cardiac ejection is composed of two parts: non pulsatile components and pulsatile components. The former is peripheral resistance, while the latter is produced by the effects of arterial compliance and reflected waves. When arterial stiffness increases, due to speed up and reflection points of pulse wave velocity to near the heart, reflected wave appeared earlier in the systolic pressure curve, which increased systolic blood pressure and pulse pressure, reduced diastolic pressure, resulting in increased left ventricular afterload and easily leading to left ventricular hypertrophy. Because the coronary blood supply mainly depends on the diastolic pressure and the length of diastole, diastolic blood pressure lowering can lead to coronary hypoperfusion. Increased left ventricular afterload causes an increase in left ventricular oxygen demand, and perfusion of the left ventricle is decreased due to coronary insufficiency. Both of the two can aggravate myocardial ischemia and hypoxia, resulting in ischemic heart disease. In fact, it has been shown that the increase of aortic stiffness, reflex wave and pulse pressure in patients with essential hypertension is closely related to left ventricular hypertrophy in patients. Atherosclerosis can change the pulse wave transmission and reflection, causing systolic hypertension. Therefore, it can be inferred that the abnormal reflex wave caused by arterial dysfunction is an important risk factor for cardiovascular disease.

3.2. Selection of characteristic points of pulse wave signal

Human pulse wave is generally considered to have 6 characteristic points, as shown in Fig. .1. Point b1 is the opening point of aortic valve, point c1 is the highest systolic pressure point, point d is the aortic dilation pressure point, point e is the starting point of left ventricular diastolic, point f is the starting point of anti-tidal wave, and point g is the highest pressure point of the anti-tidal wave. They reflect different states of the cardiovascular system.

In the analysis of the experimental results, through the analysis of the relationship between the characteristics of the points, the difference between patients and normal people is compared. Based on the recognition of pulse feature point, we define the index as shown in Fig. 2. The left one is the measurement of the amplitude and time interval of the pulse, and the right is the measurement for the parameters of the pulse area.

Each index is as follows: h_1 is primary wave amplitude (mm), h_2 is the amplitude of the pre-pulse wave (mm), h_3 is the lower middle lobe amplitude (mm), h_4 is pulse wave amplitude (mm), t_1 is the time from the beginning of the main wave to the peak of the main wave (ms), t_2 is the time from the beginning of the main wave to

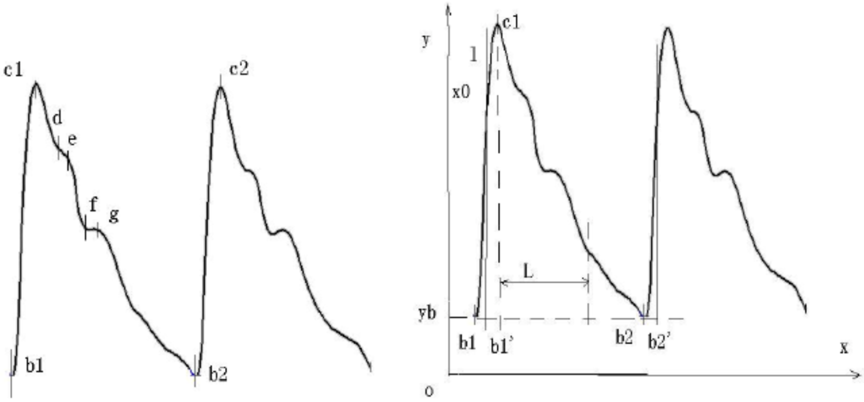

Fig. 1. The six characteristic points of pulse wave and the reference map

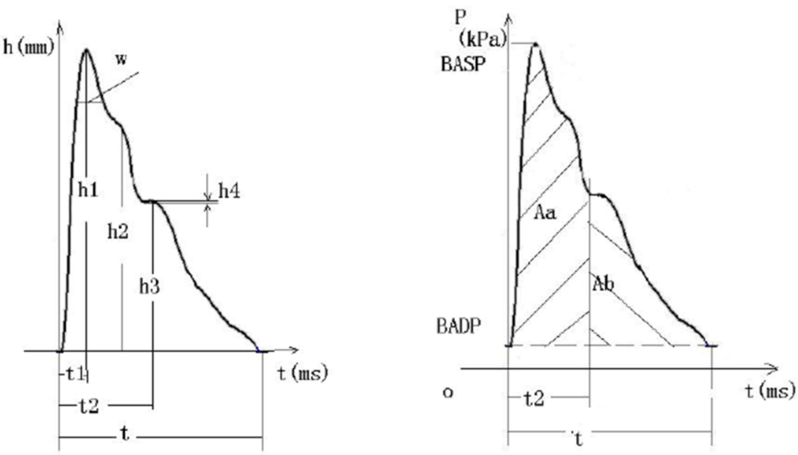

Fig. 2. Side view of pulse wave index

the bottom of the Canyon (ms), t is pulse cycle time (ms), A_a denotes the systolic area of pulse graph, and A_b denotes the diastolic area of pulse graph.

The vertical distance from the highest point to the baseline is set to h_1, and the feature normalization highly correlated with the time domain waveform of the pulse wave is h_2/h_1, h_3/h_1, and h_4/h_1, respectively. Similarly, a pulsation cycle time t is set to 1, and the time related parameters are normalized to t_2/t and t_1/t. The total area $A_\mathrm{a} + A_\mathrm{b}$ of the pulse wave time domain waveform is set to 1, so the area related parameters can be normalized to area $A_\mathrm{a}/(A_\mathrm{a} + A_\mathrm{b})$.

3.3. Study on fuzzy pattern recognition using genetic algorithm

From any initial population of genetic algorithm, populations evolve from generation to generation for better areas until the optimal solution with the genetic operations of selection, crossover and mutation. Because of its inherent parallelism and not easy to fall into local optimum, it is very suitable for large scale space search optimization. The first step: input control parameters: population size P, crossover probability C, and mutation probability M.

The second step: the initial population G is generated randomly, and the fitness of each individual in the population and the total fitness of the population are calculated.

The third step: genetic operators (that is, selection, crossover, mutation) are used to produce a new generation G of groups, and calculate individual fitness, in order to evaluate the individual.

The fourth step: convergence condition judgment. If the average fitness difference of adjacent generations is less than a threshold ε or the specified evolution algebra is completed, the search is terminated. According to the fitness, the results are sorted by the individual, and the highest fitness value is selected as the optimal solution. Otherwise, turn to the third step.

4. Result analysis and discussion

4.1. Experimental method

From April 2007 to June 2007, form patients in the Second Department of Cardiology, the Second Affiliated Hospital of Tianjin University of Traditional Chinese Medicine, and sixty eligible patients were selected and included in this study. There were 30 cases in the control group and the others in the control group. The test instrument was calibrated before the measurement. The subjects' name, sex, height, weight and other basic parameters were input into the computer. The subjects sat for 15 minutes before the test. The instrument was used to record the pulse wave of the left wrist of the tested person and save into the computer. Patients for echocardiographic measurements should be given a brief rest before the examination to avoid tension and activity affecting blood flow velocity. Echocardiography included two-dimensional, M type and Doppler echocardiography, with probe frequency of 2.5 MHz.

4.2. Verification of time domain feature recognition model of pulse wave

In this paper, the fitness function of genetic algorithm optimization was Fisher criterion function. According to the definition of Fisher criterion function, the feature selection program of the Matlab genetic algorithm was compiled, and the Fisher criterion function was returned. The criterion was that if the value of Fisher criterion function was more than 0.5, it was considered as feature selection; otherwise, it would be removed out. As shown in Table 1, the Fisher criterion function values returned by each parameter for parameters feature selection of the pulse wave time domain were listed.

Table 1. Fisher criterion function of time domain parameter

h_2/h_1	h_3/h_1	h_4/h_1	t_1/t	t_2/t	$A_a/(A_a+A_b)$
0.9355	0.7942	0.9669	0.602	0.4733	0.6595

According to the results of the above table, we could see that, in addition to t_2/t, other parameters were up to the selection criteria, which could be used as the selected parameters of the next model training. The model test results are shown in Fig. 3.

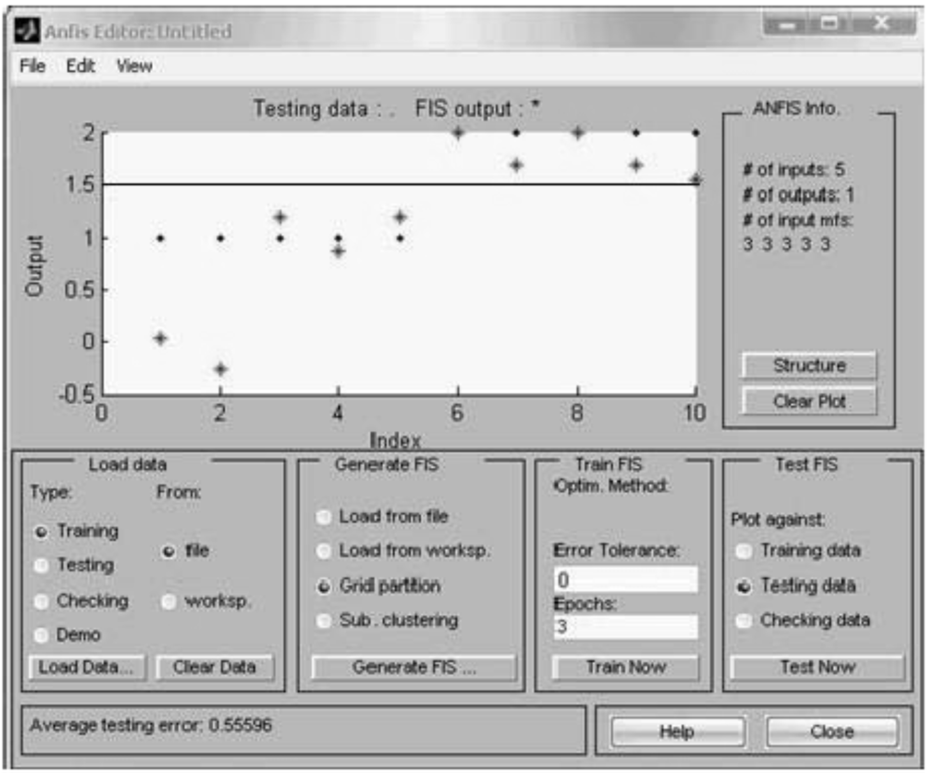

Fig. 3. Test results of fuzzy recognition model

Set the results of the classification threshold: the patient classification code was set to 1, and the normal classification code was set to 2. In the results of the model training, if the test sample classification code identification was less than 1.5, the sample was more close to category 1; if more than 1.5, the sample was more close to category 2.

5. Verification of frequency domain feature recognition model of pulse wave

In this paper, the fitness function of genetic algorithm optimization was Fisher criterion function. According to the definition of Fisher criterion function, the feature selection program of the Matlab genetic algorithm was compiled, and the Fisher criterion function was returned. The criterion was that if the value of Fisher criterion function was more than 0.5, it was considered as feature selection; otherwise, it would be removed out. As shown in Table 2, the Fisher criterion function values returned by each parameter for parameters feature selection of the pulse wave frequency domain were listed.

Table 2. Fisher criterion function of frequency domain parameter

Pera6	Pera5	Pera4	Pera3	Pera2	Pera1	we
0.4057	0.5678	0.6458	0.9159	0.9862	0.6049	0.9781

According to the results of Table 2, we could see that all parameters except the pulse wave frequency domain Pera6 achieved the optimization criteria, which could be used as the parameters of the next model training. The Fisher criterion function value of Perd3, Perd2 and we was the largest, which indicated that the spectral energy of the pulse wave signal in the interval of the pulse wave frequency range of 5–20Hz was smaller than that of the pulse wave signal, known as wavelet entropy. The pathological features of the patients with obvious coronary heart disease and normal subjects were included.

Table 3 showed the coordinates of the center of gravity of each category in space. After the calculation of the specific coordinates of each observation and their distance from the center of gravity, we could determine their classification.

Table 3. Barycentric coordinates of each category (1 for patients with coronary heart disease, and 2 for normal persons)

Group	Function
1.00	–1.084
2.00	1.084

It could be seen from Table 3 that the correct rate of the recognition of coronal heart disease patients and normal persons was 83.3 % and 90 %, respectively. The results of cross validation showed that the pulse wave characteristic parameters could be used to distinguish between patients with coronary heart disease and normal subjects.

6. Verification of hybrid feature recognition model

The parameters of pulse wave frequency domain and time domain of 30 patients with coronary heart disease and 30 normal subjects were selected as the training samples. The marker variable group was used to divide them into two groups, namely, the coronal heart disease patients and the normal subjects. Table 4 shows the coordinates of the center of gravity of each class in space. As long as we could calculate the coordinates of each observation in the front and the distance from the center of gravity, we could know their classification.

Table 4. Barycentric coordinates of each category (1 for coronary heart disease, and 2 for normal persons)

Group	Function
1.00	–1.298
2.00	1.298

The results of the evaluation of the model performance by interactive verification were shown in Table 5.

Table 5. Correct classification of interactive verification)

Classification	Patients with coronary heart disease	Normal persons
Patients with coronary heart disease	80.0 %	20.0 %
Normal persons	16.7 %	83.3 %

It could be seen from Table 6 that the correct rate of the recognition of coronal heart disease patients and normal persons was 80 % and 83.3 %, respectively. The results of cross validation showed that the pulse wave characteristic parameters could be used to distinguish between patients with coronary heart disease and normal subjects.

6.1. Conclusion

In this paper, the method of pulse wave signal in time domain and frequency domain parameters identification of cardiovascular disease patients and normal persons was studied, which were mainly focused on the definition and selection of parameters of pulse wave in time domain and frequency domain, parameter optimization and the establishment of identification model. The clinical trial data as the basis of this research, the echocardiographic results of echocardiography and ECG results measured by multi lead ECG as the basis for clinical diagnosis of patients with coronary heart disease, the criteria for screening patients with coronary heart disease were as criteria for screening cases. Under the premise of this standard, the original pulse wave shape data of patients with coronary heart disease and normal people were collected, and the parameters of time and frequency domain were calculated.

The method of feature selection based on genetic algorithm was used to optimize the parameters of pulse wave. By setting the value of Fisher criterion function, the characteristic parameters of the return criterion function value less than 0.5 were removed. To some extent, the composition of the pulse wave characteristic parameters was optimized, which laid a good foundation for the establishment of the model. This method was suitable for feature selection with a large number of feature parameters. In this paper, genetic algorithm was introduced to optimize the parameters of human pulse wave information, which laid a foundation for future research work.

A preliminary study on the diagnosis of coronary heart disease by using the parameters of time and frequency of pulse wave and the establishment of the model of feature recognition was made in this paper. The results of this study achieved the primary objective of the theory. However, due to the problem of small sample size, the correction of the model and the improvement of the recognition accuracy needed to be further implemented. For the first time, the complexity parameter was introduced into the field of pulse wave analysis. However, there are many more analytical methods can be applied to the analysis of pulse wave signal, and further research is needed in the future research.

References

[1] J. M. Jornet, I. F. Akyildiz: *Femtosecond-long pulse-based modulation for terahertz band communication in nanonetworks.* IEEE Transactions on Communications *62* (2014), No. 5, 1742–1754.

[2] A. S. Liberson, J. S. Lillie, W. S. Day, D. A. Borkholder: *A physics based approach to the pulse wave velocity prediction in compliant arterial segments.* Journal of Biomechanics *49* (2016), No. 14, 3460–3466.

[3] X. Chen, J. Li, Z. Zhang, Y. Wang, Z. Jia, K. Pu, D. Yu: *A new algorithm for calculating optimal viewing angles in coronary angiography based on 4-D cardiac computed tomography.* Journal of X-ray science and technology *22* (2014), No. 2, 137–145.

[4] R. Singh, A. Khare: *Fusion of multimodal medical images using Daubechies complex wavelet transform–A multiresolution approach.* Information Fusion *19* (2014), 49–60.

[5] C. W. Chang, S. H. Wang, M. Y. Jan, W. K. Wang: *Effect of black tea consumption on radial blood pulse spectrum and cognitive health.* Complementary Therapies in Medicine *31* (2017), 1–7.

[6] U. R. Acharya, H. Fujita, V. K. Sudarshan, S. Bhat, J. E. W. Koh: *Application of entropies for automated diagnosis of epilepsy using EEG signals: A review.* Knowledge-Based Systems *88* (2015), 85–96.

[7] H. Xiao, I. Tan, M. Butlin, D. Li, A. P. Avolio: *Arterial viscoelasticity: Role in the dependency of pulse wave velocity on heart rate in conduit arteries.* American Journal of Physiology-Heart and Circulatory Physiology *312* (2017), No. 6, H1185–H1194.

[8] M. U. Qureshi, VG. D. A. Vaughan, C. Sainsbury: *Numerical simulation of blood flow and pressure drop in the pulmonary arterial and venous circulation.* Biomechanics and modeling in mechanobiology *13* (2014), No. 5, 1137–1154.

[9] X. Lu, G. V. Naidis, M. Laroussi, K. Ostrikov: *Guided ionization waves: Theory and experiments.* Physics Reports *540* (2014), No. 3, 123–166.

[10] D. Wang, D. Zhang, G. Lu: *A novel multichannel wrist pulse system with different sensor arrays.* IEEE Transactions on Instrumentation and Measurement *64* (2015), No. 7, 2020–2034.

[11] S. Y. Shin, E. B. Fauman, A. K. Petersen, J. Krumsiek, R. Santos, J. Huang, M. Arnold, I. Erte, V. Forgetta, T. P. Yang, K. Walter, C. Menni, L. Chen, L. Vasquez, A. M. Valdes, C. L. Hyde, V. Wang, D. Ziemek, P. Roberts, L. Xi, E. Grundberg, (MuTHER) Consortium, M. Waldenberger, J. B. Richards, R. P. Mohney, M. V. Milburn, S. l. John, J. Trimmer, F. J. Theis, J. P. Overington, K. Suhre, M. J. Brosnan, C. Gieger, G. Kastenmüller, T. D. Spector, N. Soranzo: *An atlas of genetic influences on human blood metabolites.* Nature genetics *46* (2014), 543–550.

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