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Research on coupling relationship between ECG and PW signal in the cardiovascular system

Fangfang Jiang*, Shaoxiu Song, Jiabin Cheng, Siliang He and Xiao Yang
Sino-Dutch Biomedical and Information Engineering School, Northeastern University, Shenyang, Liaoning, China

Abstract.
BACKGROUND: Cardiovascular disease (CVD) has become the main cause of morbidity and mortality world-wide.
OBJECTIVE: In order to obtain the potential function of cardiovascular system information further, the parameters of the coupling relationship between Electrocardiogram (ECG) signal and Pulse Wave (PW) signal are proposed.
METHODS: In this paper, we detected the peaks of ECG and PW signal synchronously from the Fantasia database using Empirical Mode Decomposition (EMD) algorithm, and analyzed the interval between different age groups in the same domain, then calculating the Euclidean distance to characterize the coupling relationship.
RESULTS: Via the experimental results of 20 subjects, the parameters of the old group were always larger than the young group. Thus the synchronization and consistency for PW following the ECG are weaker than the young group, which is in keeping with the clinical rule.
CONCLUSIONS: The conclusion is that there is a certain representation for the cardiovascular system with the coupling relationship parameter proposed.

Keywords: ECG, PW, coupling relationship, cardiovascular system, EMD

1. Introduction

Currently, CVD has become the main cause of morbidity and mortality world-wide [1]. Hypertension and coronary artery disease resulting from the development of arteriosclerosis are two major causes of CVD. Arteriosclerosis is a vascular disease in which aortic stiffness shows excessive increases resulting from long-term consequences of poor lifestyle habits and aging. Atheromatosis occurs in large and medium-sized arteries with progression of arteriosclerosis. It causes arterial stenosis and reduced blood flow to tissues, resulting in the development of various disorders. By the time serious symptoms are detected, arteriosclerosis is usually quite advanced, having progressed for decades. There is, therefore, increased emphasis on early detection of arteriosclerosis and atherosclerosis and their prevention by modifying risk factors using strategies such as healthy eating, exercise and avoidance of smoking [2–5].

Physiological signals such as PW, ECG and blood pressure (BP) have been used as guides to judge physical condition of human body and diagnose various diseases for many years [6,7]. The morphology

*Corresponding author: Fangfang Jiang, Northeastern University H004 Mailbox, Zhihui Street No.500, Hunnan District, Shenyang, Liaoning, China. Tel.: +86 13898826213; Fax: +86 024 8368 8859; E-mail: jiangff@bmie.neu.edu.cn.

of PW and ECG are influenced by many factors such as the diastolic and systolic movement of the aorta, the agitation of arteries and blood caused by the heart's pumping action [8,9].

In this paper, we studied the morphology variability and the coupling relationship between PW and ECG.

2. Methods

2.1. Fantasia database

Fantasia database is internationally recognized as one of the standard ECG database which is established by MIT-BIH. Twenty young (21–34 years old) and twenty elderly (68–85 years old) rigorously-screened healthy subjects underwent 120 minutes of continuous supine resting while continuous ECG, and respiration signals were collected synchronously; in half of each group, the recordings also include an uncalibrated continuous non-invasive PW signal. Each subgroup of subjects includes equal numbers of men and women. All subjects remained in a resting state in sinus rhythm while watching the movie Fantasia (Disney, 1940) to help maintain wakefulness. The continuous ECG, respiration, and (where available) PW signals were digitized at 250 Hz. Records f1y01, f1y02, ... f1y10 and f2y01, f2y02, ... f2y10) were obtained from the young subjects, and records f1o01, f1o02, ... f1o10 and f2o01, f2o02, ... f2o10) were obtained from the elderly subjects.

Each subject has a [.dat] document and a [.hea] document. The header line is called recode line, which includes the name of the signal, the quality of the signal, the frequency of sampling, and the amount of the sampling signal, the time of the sampling signal. Take f1o01.hea for example:

f2o01 3 250 1752809
f2o01.dat 212 819.2 12 0 99 15208 0 RESP
f2o01.dat 212 819.2 12 0 17 18581 0 ECG
f2o01.dat 212 819.2 12 0 88 -30441 0 BP
Age: 73 Sex: F

The first line includes the following information: 3 means there are three signals, 250 means the sample frequency is 250 Hz, and 1752809 means the length of each sampling signal.

[.dat] document is coded with Format212 to store data. Format212 is a kind of data storage format, which alternate storage two signals by each of the three bytes.

2.2. The importing of PW signal and ECG signal

Two signals are imported with MATLAB, commercial mathematics software, which is developed by the MathWorks in U.S. for algorithm development, data visualization, data analysis and numerical calculation senior technical computing language and interactive environment.

The [.dat] document and [.hea] document are imported respectively. And then set the shift bytes to find the sampling point of signal, finally figure out ECG and PW waveform. The ECG and PW signal showed in Fig. 1. The abscissa is sampling points, and the ordinate is amplitude with volt.

2.3. Measurements of the PW interval and ECG interval

The ECG interval sequence and PW diastolic interval sequence are research objects. R-wave is the highest waveform in ECG, and easy to be detected. In general, adjacent R wave is regarded as cycle

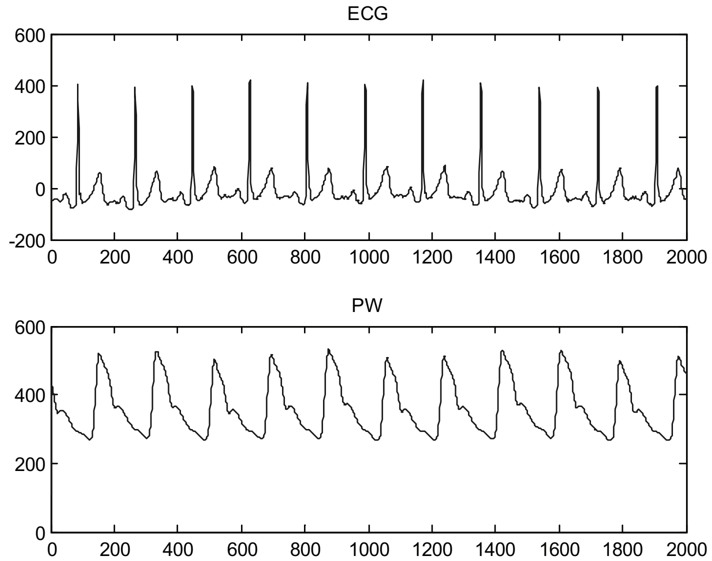

Fig. 1. PW signal and ECG signal.

flag. The interval of RR is regarded as ECG interval. After finding R wave, PW diastolic interval can be determined.

The traditional methods of data processing, such as the Fourier Transform and Wavelet Transform, are based on the assumptions that the study data is linear or stable. In order to analyze the nonlinear and non-stationary data, Hilbert-Huang Transform (HHT) is submitted by professor Norden et al. [10,11] in 1998. HHT consists of EMD and Hilbert spectral analysis. It bases on a method of adaptive processing data and is a unique method of a non-stationary analysis.

In this paper, EMD is applied to calculate the interval of PW and ECG, whose flow chart is in Fig. 2. EMD can process data in the frequency domain and adaptively transform the signal into some intrinsic mode functions (IMFs).

$x(t)$ is decomposed with EMD as Formula (1):

$$x(t) = \sum\nolimits_{j=1}^{n} c_j(t) + r_n(t) \tag{1}$$

In the formula $c_j(t)$ represents the component of IMFs, $r_n(t)$ represents the remnant. The algorithm flow is as follows:

(1) Assume $r_0(t) = x(t), j = 1$
(2) Extract j^{th} IMF component
  a. Assume $h_0(t) = r_{j-1}(t), i = 1$
  b. Find the local maxima and minima of $h_{i-1}(t)$
  c. Interpolate to find the envelope $e_{\max}(t)$ and $e_{\min}(t)$ according to the extreme points which have been found
  d. Calculate the mean of envelope as $m_{i-1}(t) = [e_{mac}(t) + e_{\min}(t)]/2$
  e. $h_i(t) = h_i(t) - m_{i-1}(t), j = j{+}1$
  f. Repeat (b–e) until $h_i(t)$ satisfies the condition of IMF. And then assume $c_j(t) = h_i(t)$
(3) $r_j(t) = r_{j-1}(t) - c_j(t), j = j{+}1$

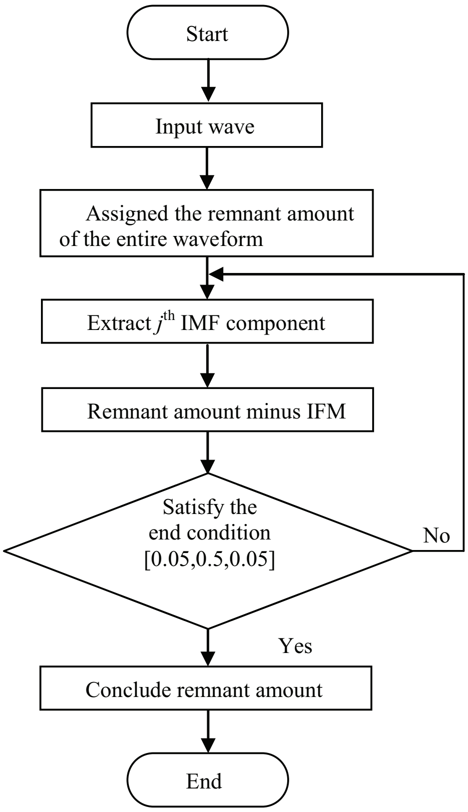

Fig. 2. The flow chart for decomposition process of EMD.

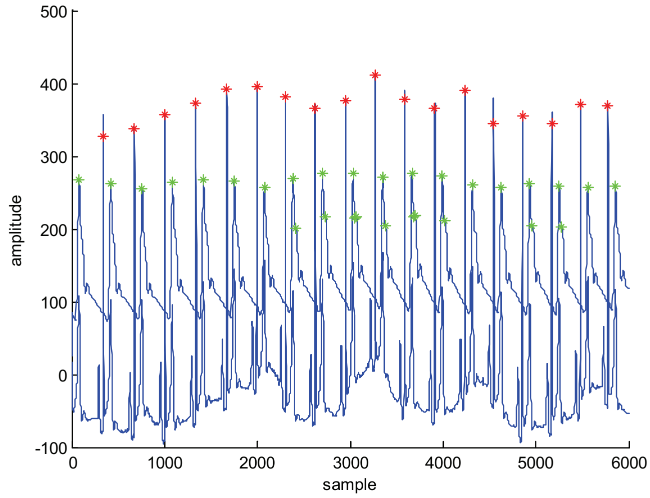

Fig. 3. The original maxima point of the signal.

(4) Repeat (2, 3) until $r_j(t)$ satisfies the end condition.

Each IMF component is transformed by HHT.

Take f2o06 as an example to illustrate how to extract the R position with EMD method. The following is the steps.

(1) Import the ECG signal from the database;
(2) Decompose the ECG signal with the method of EMD according to the end condition of HHT;
(3) Process the IMF obtained components for non-linear with Formula (2);

$$y(n) = \begin{cases} |x(n) * x(n-1) * x(n-2)|, & x(n)x(n-1)x(n-2) \text{ have the same sign} \\ 0, & \text{others} \end{cases} \tag{2}$$

$x(n)$ represents each IMF component.;

(4) Process the IMF with smoothing window using Formula (3);

$$z(n) = \frac{1}{M}(y(n-(M-1)) + y(n-(M-2)) + \ldots + y(n)) \tag{3}$$

M represents the size of the smoothing window;

(5) Find the maxima which can be regarded as original R point to use low pass filter;
(6) Find the final R-point which is the maximum point in the original 10 R points;

Table 1
Part of subjects' interval of ECG and PW signal

Number		Signal	Standard deviation	The interval time of ECG and PW (s)					
Young	1	PW	0.0453	0.860	0.856	0.852	0.936	0.084	0.0812
				0.836	0.884	0.868	0.852	0.792	0.752
				0.796	0.812	0.880	0.812	0.844	0.900
				0.796	0.832	0.880	0.884	0.816	0.836
				0.840	0.776	0.740			
		ECG	0.0427	0.864	0.840	0.864	0.928	0.800	0.828
				0.832	0.884	0.864	0.848	0.784	0.768
				0.796	0.812	0.872	0.820	0.840	0.892
				0.804	0.836	0.880	0.872	0.824	0.840
				0.836	0.764	0.760			
	2	PW	0.0917	1.392	1.408	1.324	1.212	1.312	1.564
				1.500	1.328	1.336	1.396	1.384	1.284
				1.384	1.500	1.320			
		ECG	0.0844	1.400	1.400	1.312	1.232	1.316	1.560
				1.488	1.322	1.344	1.396	1.376	1.288
				1.352	1.492	1.316			
	3	PW	0.0264	1.056	1.068	1.028	1.064	1.072	1.020
				1.056	1.052	1.016	1.040	1.048	1.016
				1.040	1.048	1.004	1.012	1.020	0.980
				1.008	1.020	1.024	0.984		
		ECG	0.0259	1.060	1.060	1.032	1.072	1.064	1.024
				1.056	1.052	1.016	1.04	1.048	1.012
				1.044	1.048	1.000	1.020	1.012	0.984
				1.008	1.020	0.984	1.024		
	4	PW	0.0191	0.764	0.764	0.756	0.774	0.732	0.748
				0.764	0.764	0.736	0.756	0.764	0.732
				0.736	0.756	0.760	0.732	0.760	0.772
				0.780	0.780	0.774	0.724	0.724	0.720
				0.708	0.724	0.736	0.720	0.736	0.760
		ECG	0.0185	0.768	0.760	0.756	0.740	0.736	0.752
				0.764	0.756	0.740	0.760	0.764	0.728
				0.752	0.752	0.756	0.736	0.764	0.768
				0.784	0.776	0.740	0.728	0.728	0.716
				0.712	0.728	0.732	0.720	0.736	0.760

(7) Find the interval of the ECG signal which is the adjacent R point;

Figures 3 and 4 show the resultant waveforms from applying EMD to get the peak point in the signal from f2o06 in Fantasia database.

3. Experiments

To study the coupling relationship between ECG and PW signal in the cardiovascular system, it is necessary to calculate the interval time of synchronization ECG and PW signal. Thus we apply EMD method to find the peak points from ECG and PW signal, and research the coordinate values of peak points firstly. Secondly, calculate the X-coordinate distance of adjacent peak point, and the sampling frequency of the signal can be achieved from .hea which is 250 Hz. Finally, determine the distance divides 250 as the interval of ECG and PW signal. Table 1 shows the intervals of ECG and PW signal we calculated from part of database.

Table 2
The coupling relationship between ECG and PW

Number		S	Number	S	Number		S	Number	S
Young	1	0.0017	6	0.000852	Old	1	0.0014	6	0.0098
	2	0.0022	7	0.0015		2	0.0011	7	0.004
	3	0.0012	8	0.00085		3	0.0052	8	0.0025
	4	0.000718	9	0.0018		4	0.0053	9	0.0012
	5	0.0034	10	0.000602		5	0.00048	10	0.000795

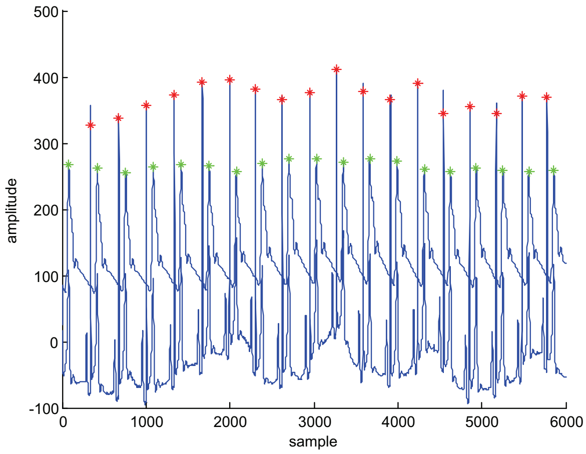

Fig. 4. Interval refinement of signals.

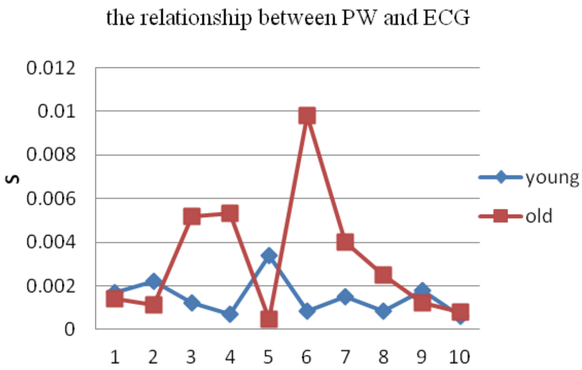

Fig. 5. The chart of relationship between PW and ECG signal.

In the Table 1, the time intervals of ECG and PW are acquired in the same data segment, and it can ensure the ECG and PW signal comparability. These signals are acquired from the interval point of 10000 to 18999 in the database. In the point interval, the next step is to process these signals, and to get the interval of ECG and PW signal and the standard deviation of the interval.

First of all, the standard deviation is calculated. And then get the Euclidean distance of adjacent peak point in the corresponding region of ECG and PW signal. The formula of the Euclidean distance(S) is shown as Formula (4):

$$S = \sqrt{\sum_{k=1}^{n} |(PW_k - ECG_k)^2|} \tag{4}$$

In the formula, PW_k represents the interval of PW signal, and ECG_k represents the interval of ECG signal, and n represents the number of PW interval.

Moreover, calculate the S by the Formula (4), the results show in Table 2.

In Table 2, it includes all the information of subjects in Fantasia database, and then to demonstrate the coupling relationship better between the old subjects and young subjects. The relation between PW and ECG is draw as a chart, which is shown in Fig. 5.

In Fig. 5, the X-coordinate represents the number of the subjects, and the Y-coordinate represents S. The blue line represents the coupling relationship of young subjects, and the red line represents the coupling relationship of old subjects. Contrast the two lines, we summarize the following results:

(1) The mean S value of the old people group is higher than the young group;

(2) According to (1), it shows that the old group synchronization and consistency PW following the ECG is weaker than the young group;
(3) The ECG and PW signal have the coupling characteristics;
(4) It is feasible to use this parameter to analysis the cardiovascular performance.

4. Conclusion

The experiment results prove that it is feasible to use this parameter to analysis the cardiovascular performance and the algorithm we proposed has confirmed that the old group synchronization and consistency PW following the ECG is weaker than the young group.

An understanding of cardiovascular alterations is crucial to interpret the adaptive mechanisms the coupling relationship between PW and ECG. The values of two signals' interval can reflect the human health. In this paper, we chose the subjects from Fantasia database which have collected the PW and ECG. In future, it is necessary to design a device to real-time collect these signals with different subjects and then analysis the coupling relationship between the signals synchronously. It will be more convince and significative.

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