

Singularity detection of the rabbit electrocardiogram: An evolutionary spectral method

Xinyuan Liu^{a,*}, Dingwu He^a, Liuqing Pei^b, Suming Zhang^a

^a School of Electronics Engineering and Computer Science, Peking University, Beijing 100871, China

^b College of Information Science and Engineering, Beijing Normal University, Beijing 100875, China

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Abstract

The time–frequency characteristics of the spectral density of non-stationary signals (NSS) in the neighborhood of an instant time point can be determined using the evolutionary spectral analysis. An experimental rabbit model involving ligation of the left anterior descending coronary artery to simulate the physiology of early phase myocardial ischemia (EPMI) has been previously described. Clinically, EPMI derived from left coronary artery stenosis is the main symptom of coronary heart diseases including acute myocardial infarction. Here, we propose a new algorithm for estimating the evolutionary spectral density functions, which is an effective approach to determine the instantaneous frequency spectra (IFS) of NSS under the uncertainty principle in the time–frequency domain. The localization singularity information in the data recorded from a living system could be detected by means of the IFS. Electrocardiogram (ECG) data recorded from experimental rabbits were analyzed with the new algorithm. Results showed that the Q 's value of the evolutionary spectral quality number of the QRS-complex data was the characteristic parameter of ECG, and there was a matched connection between the time–frequency characteristics of QRS-complex data and the myocardial ischemia symptoms of the rabbits. These results provide valuable information regarding features of the EPMI for use in clinical diagnoses.

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1. Introduction

Coronary heart disease is one of the main diseases threatening human health. According to the 1996 report from the American College of Cardiology (ACC), one person in the USA died from cardiovascular diseases every 33 s, and 70% of these died from coronary heart disease. The data published by the National Center for Cardiovascular Diseases (NCCD) of China on November 1, 2006 showed that approximately 2.5–3.0 million people died from cardio-cerebral vascular diseases every year (7000 people every day), and approximately 540,000 people died

from cardiac sudden death in China every year; and the number of young and middle-aged victims is increasing. Therefore, the ability to identify and predict some of these diseases will help to reduce these high rates of mortality.

Inherency information of data from living systems is generally contained in the non-stationary signals such as electroencephalogram (EEG), electrocardiogram (ECG), and magnetocardiogram (MCG). The auto-covariance function and the power spectral density of the non-stationary signals are time dependent. Singularity detection of ECG has been used for clinical diagnosis of heart diseases, and can provide some information of the cardiology [1]. However, the basic characteristics of information from traditional ECG signal analysis methods concern morphological changes and waveform amplitude in the time domain,

* Corresponding author. Tel.: +86 10 62759324.
E-mail address: xinyuanliu@pku.edu.cn (X. Liu).

and as such, there is potential for inter-observer variability of subject results. The work of Langner et al. [2] on the frequency domain analysis method of ECG signals has received renewed interest [3,4], with recent studies showing that the analysis method of the time–frequency domain is a novel approach to further identify the characteristic information of ECG and MCG signals [5]. Importantly, the time–frequency characteristics of ECG signals can reveal some changes in cardiac physiology [6–8]. Based on the concept of the evolutionary spectrum [9], in the present study, we describe a new algorithm and the procedure for estimating the evolutionary spectral density functions. An experimental rabbit model, involving ligation of the left anterior descending coronary artery (LADCA) was used to simulate the physiological states of the EPMI. Myocardial ischemia derived from the left coronary artery stenosis is the main symptom of coronary heart diseases including acute myocardial infarction [10].

2. Principle of the new algorithm for estimating the evolutionary spectral density functions

The evolutionary spectrum analysis is a time-dependent spectral method that can be used to identify the characteristics of non-stationary signals. However, the evolutionary spectrum has the same physical view point as the power spectrum of a common stationary process in that it can describe the distribution characteristics of the power spectral density of the signals in the frequency domain [9]. Moreover, it can reveal the power density distribution characteristics of the non-stationary signals in the neighborhood of an instant time point in the time–frequency domain. The traditional Fourier transform analysis represents only the overall frequency characteristics of the signals overall time and belongs to a time-independent power spectrum. As such, it only poorly detects the accurate time of the existing singularity of the signals.

Principle of the new algorithm for estimating the evolutionary spectral density functions is briefly described as follows. Based on the wavelet transform and by means of the modulated Gaussian wavelet function that has a well local field definition in the time domain and a smoothness in the frequency domain, both the three-dimensional (3D) evolutionary spectrum of the non-stationary signals in a time interval and the local time–frequency power density distributions of them at an instant time point can be determined. According to the evolutionary spectra, the instantaneous frequency density spectral characteristics of the non-stationary signals can be further detected. An outline of the new algorithm and the procedure are given as follows:

If $\Psi(t)$ is a mother wavelet which satisfies the admissible conditions, and there is a square integrable function of $x(t)$, that is $x(t) \in L^2(\mathbf{R})$, then the continuous wavelet transform of $x(t)$ is defined as the form:

$$WT_x(\alpha, b) = \frac{1}{\sqrt{\alpha}} \int_{-\infty}^{\infty} x(t)\psi^*\left(\frac{t-b}{\alpha}\right) dt \tag{1}$$

where α and b represent the transform scale and the translation parameter, respectively, and $\alpha > 0$. The expression of the frequency domain corresponding to Eq. (1) can be written as:

$$WT_x(\alpha, b) = \frac{\sqrt{\alpha}}{2\pi} \int_{-\infty}^{\infty} X(\omega)\psi^*(\alpha\omega) \exp(j\omega b) d\omega \tag{2}$$

where $X(\omega)$ and $\psi(\omega)$ are the Fourier transforms of $x(t)$ and $\psi(t)$, respectively. If we modulate the function of $x(t) \in L^2(\mathbf{R})$ by frequency ω , i.e.,

$$x'(u) = x(u) \exp(-j\omega u) \tag{3}$$

and choose an appropriate mother wavelet of $\Psi(u)$, and make the wavelet transform to the modulated function of $x'(u)$. Then the coefficient of wavelet transform should be:

$$\mu'_{j,k} = \int_{-\infty}^{\infty} x(u) \exp(-j\omega u)\psi_{j,k}^*(u) du \tag{4}$$

If we choose an appropriate weight function of w_v to weight the coefficients in Eq. (4), then the formulas for estimating the evolutionary spectral density functions are as follows:

$$h_t(\omega_m) = \sum_v w_v |\mu'_{j,k-v}|^2 \tag{5}$$

$$dH_t(\omega) = h_t(\omega_m) d\omega, \quad t \in (0, T), \quad \omega \in [\omega_{\min}, \omega_{\max}] \tag{6}$$

where $h_t(\omega_m)$ is termed the evolutionary spectral density function at the time t , which stands for the frequency spectrum of signal $x(u)$ in the neighborhood of the special time point, and ω_m is the frequency corresponding to the maximum value of $h_t(\omega_m)$. The $dH_t(\omega)$ in Eq. (6) is differentiable with respect to ω (for each t), and is termed the evolutionary spectrum of the time point t [9]. In the regions $(0, T) \times [\omega_{\min}, \omega_{\max}]$ of the time–frequency domain, the evolutionary spectrum has only one peak, and $(0, T)$ is the time region in which the singularities of the signals may exist. The ω_{\min} and ω_{\max} are the lowest and the highest frequency of the evolutionary spectrum, respectively. Eqs. (4)–(6) can be calculated by means of the recorded experimental data. Eq. (2) means that on a specific scale of α , the wavelet transform should be equivalent to a band-pass filter, of which the center frequency and the bandwidth are determined by the wavelet transform scale, and the filtering characteristics by the mother wavelet. The mother wavelet chosen in the present study is a simplified form of the Morlet-wavelet [11], of which the expression in the time domain is given by:

$$\varphi(t) = \left(\frac{1}{\sqrt{\pi\tau^2}}\right) \exp(-j2\pi f_c t) \exp\left(-\left(\frac{t}{\tau}\right)^2\right) \tag{7}$$

and its Fourier transform is the form

$$\Psi(f) = \frac{1}{\tau^2} \exp\left(-\tau^2\pi^2(f - f_c)^2\right) \tag{8}$$

The frequency spectral distribution of $\Psi(f)$ is a Gaussian, but only the center frequency is shifted to f_c , and the bandwidth is equivalent to $\Delta f = 2/(\pi\tau)$. According to the uncertainty principle in the time–frequency domain that is $\Delta t\Delta f \geq 1/(4\pi)$, we can draw the conclusion that $\Delta t \geq 1/(4\pi\Delta f) \geq \tau/8$. It should be noted that in Eqs. (7) and (8) the f , f_c , t , and τ are dimensionless frequency and time parameters; the unit frequency and unit time are both related to the sampling frequency of f_s of the recorded data. Thus, to make the wavelet transform to the analytic function of the sampling frequency of f_s , with the scale α , then the center frequency should be equivalent to $f_c f_s/\alpha$, and there are also $\Delta f = 2f_s/(\alpha\pi\tau)$ and $\Delta t \geq \alpha\tau/(8f_s)$.

3. Evolutionary spectral analysis on the experimental rabbit ECG data

3.1. Experimental data

The ECG data used in the present study were recorded from rabbit experiments performed by the State Key Laboratory for Artificial Microstructure and Mesoscopic Physics of Peking University. Experiments were performed in the magnetic shielding laboratory. Left anterior descending coronary artery (LADCA) ligation was performed on two rabbits (rabbit I and rabbit II) by a heart surgery expert, and were used to simulate the physiology of the EPMI. First, rabbits were anesthetized with pentobarbital. An ECG recorder was used to record the ECG signals from the limb lead II of both rabbits (10 kHz sampling frequency). In order to examine the characteristic information contained in the ECG data regarding the various biological electromagnetic fields of the cardiac system during myocardial ischemia, the LADCA of rabbit I was ligated at three locations; the first ligation was located near the end of the LADCA, and the second and third ligations were progressively closer to the left main coronary artery. These experimental conditions simulate the changes of the physiology of the rabbit cardiac system when myocardial ischemia is caused by multiple location stenoses of the LADCA. ECG data sets from the limb lead II of rabbit I were acquired before the first ligation, and after each subsequent ligation was made. Each data set was recorded for approximately 90–120 s, with a sampling frequency of 10 kHz. For rabbit II, after anesthesia, only one LADCA location was ligated, and 12 ECG data sets were acquired at different time intervals. This experimental design simulates the condition when myocardial ischemia of the rabbit is caused by one location stenoses of the LADCA for a long time interval.

3.2. Example of the evolutionary spectral analysis of ECG data

In this experiment, the ECG signal of rabbit I was used to investigate the distribution characteristics of the evolutionary spectra of ECG data in the time–frequency

domain, and to extract the IFS, as well as the dynamical instantaneous frequency spectral distributions (DIFSD), of the R-wave data in the ECG. Note that all of the original recorded data of the ECG used in the present study were pre-processed by eliminating the baseline drift and the noise reduced. The wavelet transform parameters were chosen as $\alpha = 200$, $\tau = 1$, and $f_c = 5$. The weight function was the normalized Hamming windows. In order to obtain the normalization results, the estimated evolutionary spectra were normalized according to formula (9):

$$nh(t_i, f_i) = h(t_i, f_i) \bigg/ \sum_{m=1}^{m=M} h(t_i, f_i) \quad (9)$$

where $nh(t_i, f_i)$ is termed the normalized evolutionary spectrum, and is applicable at the time point t_i and the frequency f_i . In Eq. (9), M and $h(t_i, f_i)$ are the frequency range of the evolutionary spectra and the evolutionary spectral density at the point of (t_i, f_i) in the time–frequency plane, respectively. A segment waveform of the ECG data and its evolutionary spectrum recorded after the experimental rabbit I was anesthetized, but prior to the first LADCA ligation, can be seen in Fig. 1(a) and (b), respectively. The relationships among the time, frequency, and power density distribution of the ECG signals in a cardiac cycle are shown as the 3D evolutionary spectrum in Fig. 1(b). The singularity information of the electromagnetic field changes of the cardiac system is contained in the spectrum. These data indicate that the evolutionary spectral density of the QRS-complex data is relatively greater, while the energy (power) concentrates mainly in the QRS-complex. According to the continuous 90 s ECG data recorded from the rabbit I before the first ligation, the corresponding evolutionary spectral sequences were obtained from where the normalized instantaneous frequency density distribution sequences of the R-wave data (R-WIFDDS; see Fig. 1(c)) in the time–frequency domain were detected, while the dynamical information of the power density spectra of the R-wave data is contained in the sequences, termed R-wave dynamical instantaneous frequency spectral distribution (R-WDIFSD), as shown in Fig. 1(c). The projected image of the R-WDIFSD in Fig. 1(c) on the f – p plane can be seen in Fig. 1(d), and can qualitatively reflect the aggregation and variability of the R-WIFS of the ECG signals in different cardiac cycles, and also reflects the rhythm and non-stationary property of the rabbits' normal ECG signals in the time domain.

Note that as yet there has been no unified concept or definition of the instantaneous frequency spectrum of the non-stationary signals. As it is constrained by the uncertainty principle in the time–frequency domain, for example, $\Delta t\Delta f \geq 1/(4\pi)$, both the Δt and the Δf can barely reach the minimum values at the same time, so both the highest resolution ratios are rarely achieved together in the time and the frequency domains. Thus determining the IFS of the non-stationary signals is a key technical difficulty. However, the evolutionary spectrum analysis can provide an

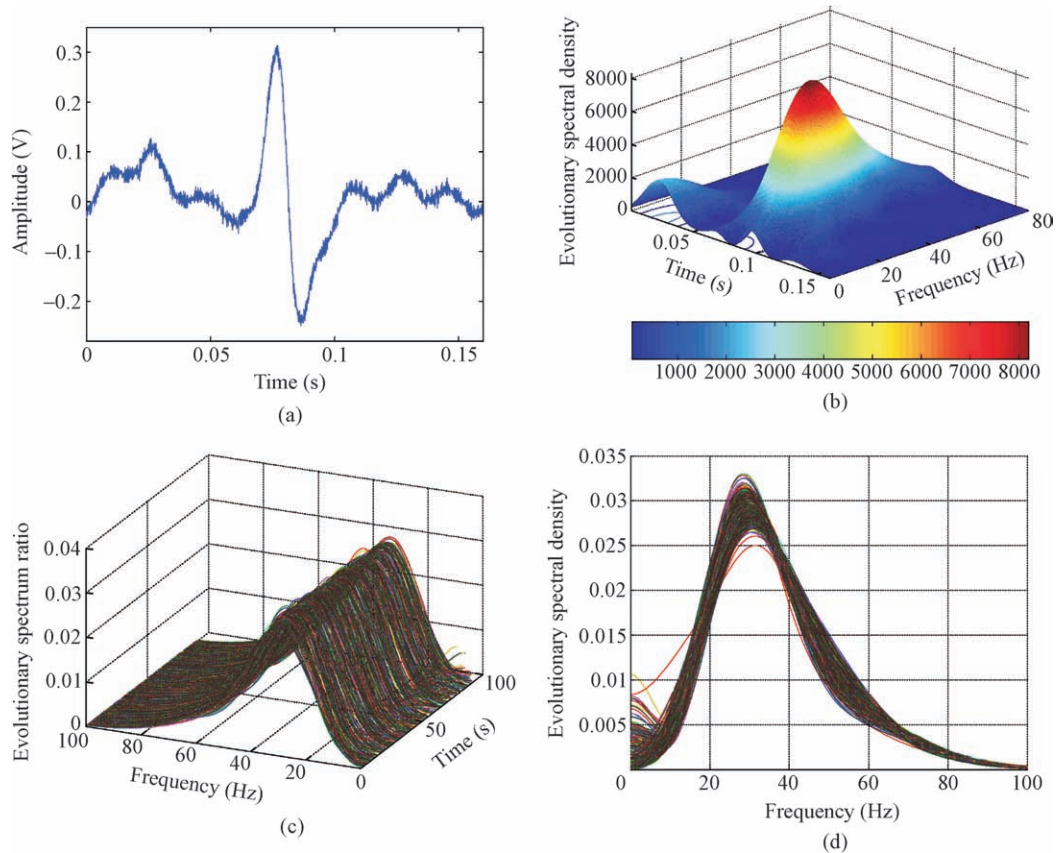


Fig. 1. (a) A segment waveform of ECG data in time recorded from rabbit I after anesthesia, but before the first LADCA ligation. (b) The 3D evolutionary spectrum of the ECG signal in a cardiac cycle. The coordinates are denoted by t -axis, f -axis, and p -axis. (c) The R-WDIFSD. (d) The projected image of the frequency spectra in (c) on the f - p plane.

efficient detecting method to overcome this problem. For example, the method to determine R-WIFS involves finding a moment time point, such as t_r , corresponding to the R-wave on the t -axis on the 3D evolutionary spectrum of Fig. 1(b), then t_r is supposed to make the f - p section that is perpendicular to the t - f plane, and the intersection set of the f - p plane and the evolutionary spectrum is the IFS at the time point of t_r . Fig. 1(c) is obtained by the orderly arrangement of the multiple R-wave normalized IFS along the time-axis, and is termed the R-WDIFSD. It should be noted that because the resolution ratios of the time and the frequency domains are under constraint by the uncertainty principle, if the “accurate instant time point” corresponding to the R-wave on the time domain is denoted as t_R , then the R-WIFS should contain some other frequency components of the ECG data in the neighborhood of time point, t_R ; the value of “ t_R ” also depends on the sampling rate of the recorded data.

3.3. Evolutionary spectral analysis on experimental rabbit ECG data

The focus of these experiments was to investigate the evolutionary spectral characteristics of the QRS-complex of the rabbit experimental ECG data. The segments of

ECG data of rabbit I and their Fourier transform frequency spectra before the first LADCA ligation and after each subsequent ligation can be seen in Fig. 2. The corresponding R-WDIFSDs can be seen in Fig. 3. A comparison of the waveforms of experimental data and their Fourier transform power spectra can be seen in Fig. 2(a) and (b), respectively. There were no significant morphological changes, although the low-frequency components increased after the first ligation. However, after the third ligation, peaked T-waves occurred in the time domain, and the low-frequency components of the Fourier transform power spectra significantly increased (Fig. 2(d)). After the third ligation ligation, the evolutionary spectra suggest that the low-frequency components (less than 10 Hz) of the R-WDIFSD significantly increased (Fig. 3(d)). These data match the Fourier transform power spectrum (Fig. 2(d)), and indicate that the non-stationary property and singularity of the ECG signals in the time domain are shown in the R-WDIFSD. The singularity information that occurs in the Fourier transform power spectra of the ECG signals is also found in the R-WDIFSD.

The segment waveform of the QRS-complex data shown in Fig. 4(a) was randomly selected from the ECG signals in Fig. 2(a), and its 3D evolutionary spectrum can be seen in Fig. 4(b). The projected image of the evolutionary

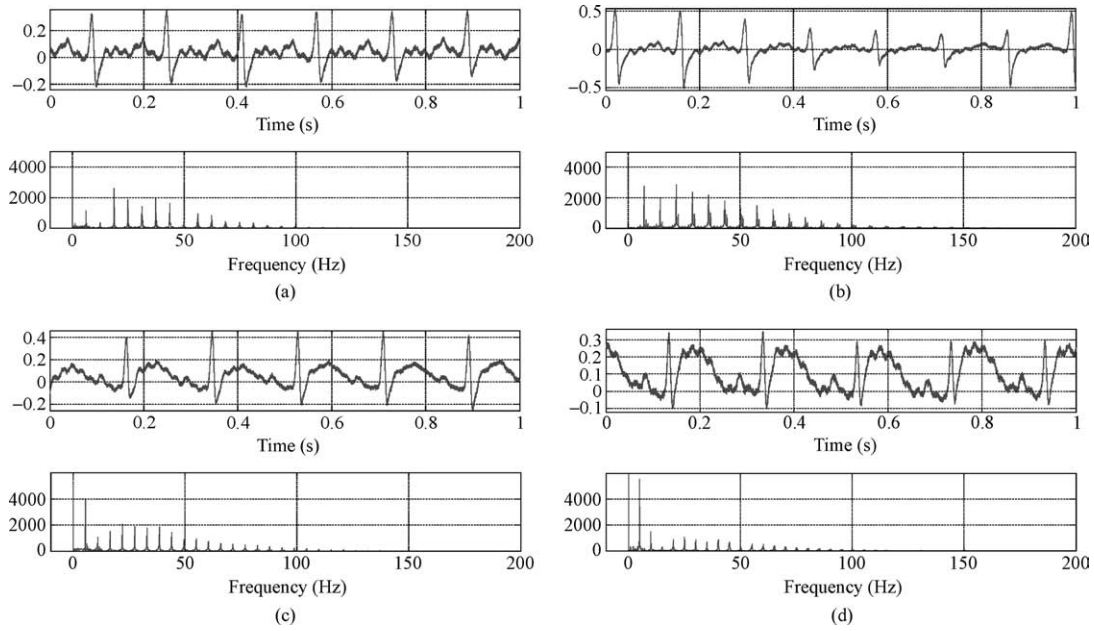


Fig. 2. ECG data segments and their Fourier transform power spectra from rabbit I before the first ligation and after each subsequent ligation. (a) Before ligation. (b) After the first location ligation. (c) After the second location ligation. (d) After the third location ligation.

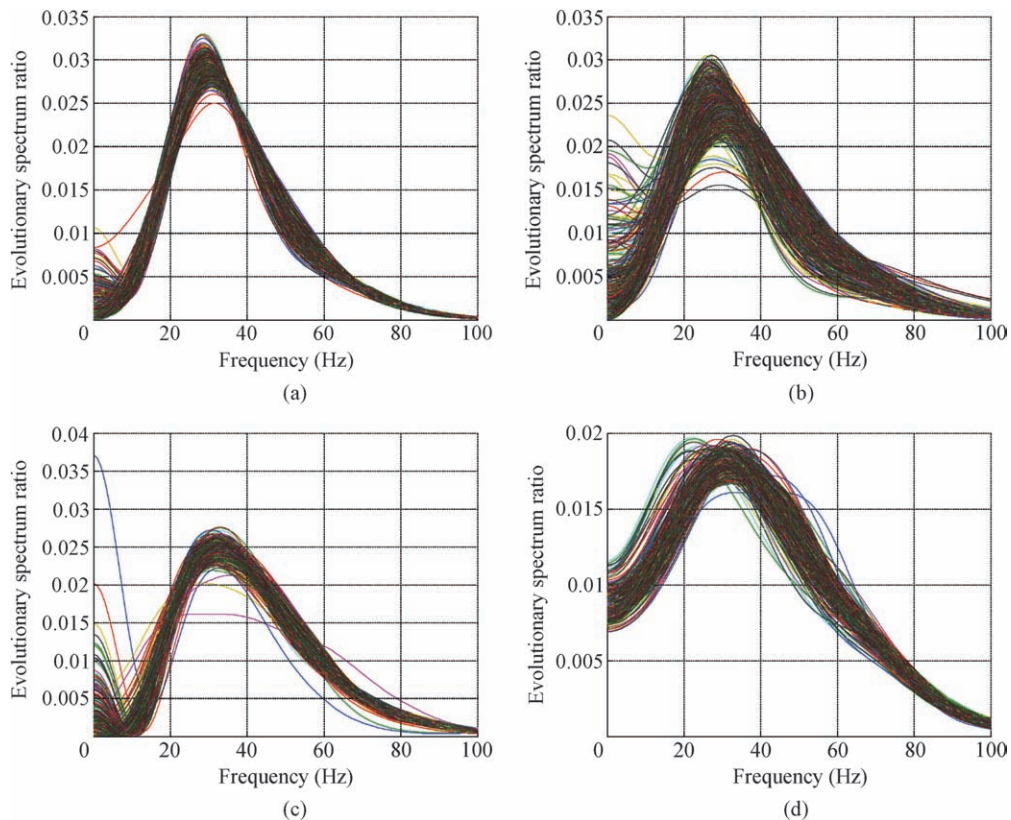


Fig. 3. The R-wave normalized dynamic instantaneous frequency spectral distribution of the ECG signals of rabbit I before and after the ligation. (a) After anesthesia and before the first location ligation. (b) After the first location ligation (datum set 1). (c) After the second location ligation (datum set 1). (d) After the third location ligation (datum set 1).

spectrum (Fig. 4(b)) on the t - f plane can be seen in Fig. 4(c). The frequency/power density spectral distribution characteristics in the range of the half-power points

in Fig. 4(b), as well as the projected image on the t - f plane, can be seen in Fig. 4(d), which is termed the evolutionary spectrum half-power points frequency spectrum distribu-

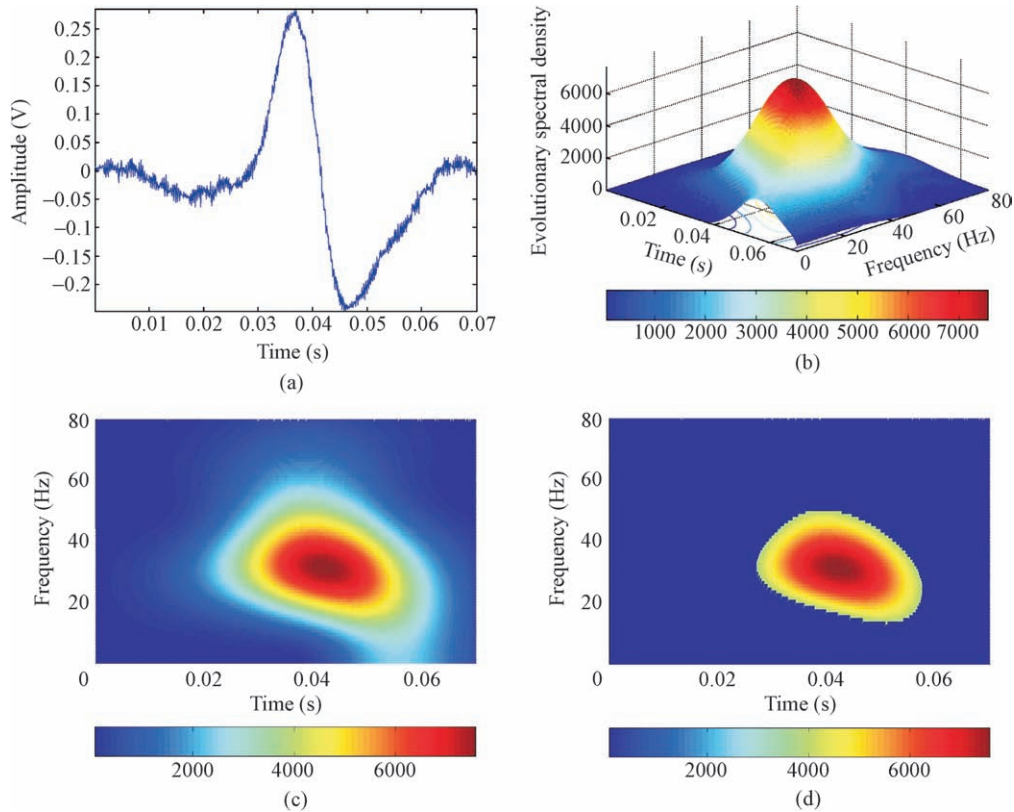


Fig. 4. A segment waveform of QRS-complex data selected randomly from the ECG signals of rabbit I before the ligation, and the evolutionary spectrum. (a) QRS-complex data. (b) The 3D evolutionary spectrum of the QRS-complex data. (c) The projected image of the evolutionary spectrum (b) on the t - f plane. (d) The ESHPFSD of the QRS-complex data.

tion (ESHPFSD). In order to further understand the basic features of the evolutionary spectra of the QRS-complex data, we defined f_H and f_L as the highest limit frequency and the lowest limit frequency of the ESHPFSD, respectively (Fig. 4(d)); the frequency of f_{cm} and the time of t_m in Fig. 4(b) are denoted at the peak location of the evolutionary spectra on the t - f plane, while the instant time that the R-wave occurs in the time domain is marked as t_r . The definition of the half-power points bandwidth is $W_b = (f_H - f_L)$. The evolutionary spectral quality number is defined as follows:

$$Q = f_{cm} / W_b \tag{10}$$

where f_{cm} , f_L , f_H , and W_b are termed the evolutionary spectral parameters, and Q is the characteristic parameter in the time–frequency domain.

As for Fig. 4, the evolutionary spectral analyses were performed on the QRS-complex data chosen from different data sets of rabbit I before the ligation. The results demonstrated that the parameter values of f_{cm} , f_H , f_L , W_b , and Q of different data sets exhibited some differences (Table 1). Before the ligation, the energy of the evolutionary spectra of the QRS-complex data from rabbit I was mainly concentrated on the frequency range of $f_L - f_H \approx 13$ –72 Hz, and the low-frequency components (≤ 10 Hz) and the higher frequency (≥ 73 Hz) were out of the ESHPFSD. Thus their energy densities were relatively lower. In the area of signal

analysis, if a function, for instance $g(x)$ or some-order derivative, is discontinuous at x_0 , then $g(x)$ has the singularity at x_0 . In the wavelet transform, if a value of the translation b equals x_0 where the singularity occurs, then the coefficient of wavelet transform of $g(x)$ should reach the amount of upper limit [12]. Therefore, t_m is equivalent to the time point when the singularity of the QRS-complex occurs. It is known from Table 1 that in the time–frequency domain the corresponding time point t_m of f_{cm} usually occurs after t_r (the R-wave occurs in the time domain), i.e., $t_m \geq t_r$. The Q 's values of the evolutionary spectral quality number of the QRS-complex data of rabbit I before the ligation basically remained at the mean level of 0.813 (the maximum relative error of Q 's values is equivalent to 16%). These data indicate that when the value of f_{cm} is changing, the value of the half-power points bandwidth of W_b changes at the same rate, and suggest that the normal cardiac system of the rabbit can maintain its rhythm by homeostasis. Further, this is the symbol of the non-stationary features of the normal ECG signals.

The segments of QRS-complex data were selected randomly from the ECG signals of rabbit I before the ligation and after each time of ligation. The corresponding ESHPFSDs can be seen in Fig. 5. There was no significant difference between before (Fig. 5(a)) and after (Fig. 5(b)) the first location ligation. The center frequency (the peak frequency of the instantaneous frequency spectrum at every

Table 1

Evolutionary spectral parameters of f_{cm} , f_L , f_H , W_b , and Q of the QRS-complex data chosen from different ECG data sets from rabbit I before the ligation.

	f_{cm} (Hz)	$(t_m - t_r)$ (s)	f_L (Hz)	f_H (Hz)	W_b (Hz)	Q
Datum set 1	31	0.0421 – 0.0370 = 0.0051	13	49	36	0.861
Datum set 2	35	0.0356 – 0.0332 = 0.0024	16	64	48	0.729
Datum set 3	38	0.0269 – 0.0256 = 0.0013	20	66	46	0.826
Datum set 4	43	0.0352 – 0.0341 = 0.0011	20	72	52	0.827

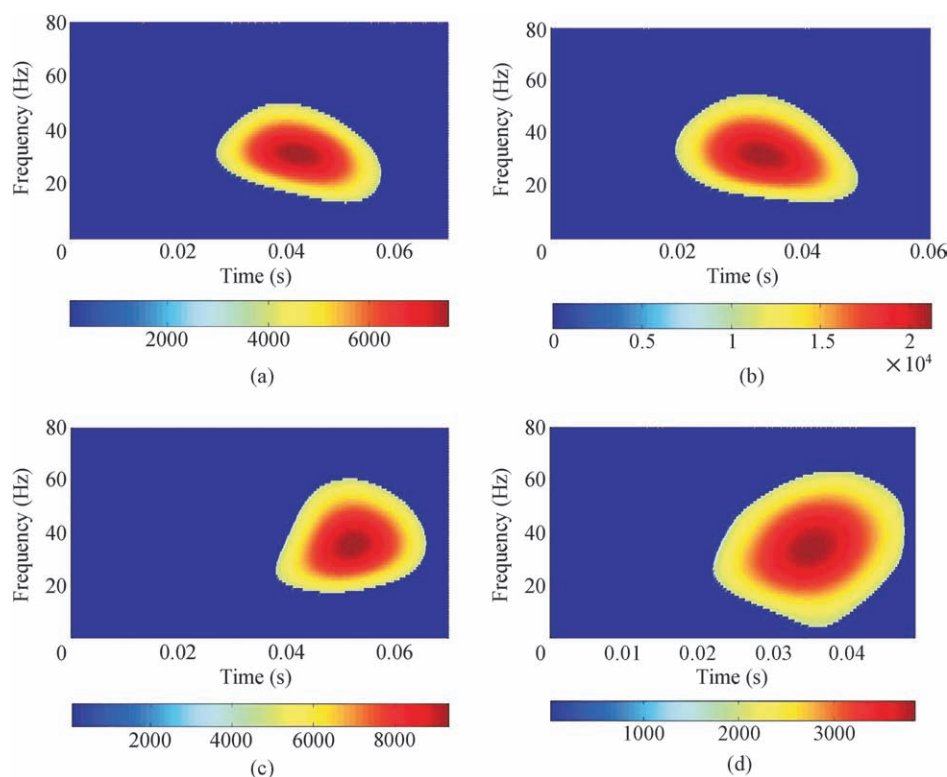


Fig. 5. The QRS-complex data selected randomly from the ECG signals of rabbit I, and their corresponding ESHPFSD figures, before the ligation and after each subsequent ligation. (a) Before the ligation. (b) After the first location ligation. (c) After the second location ligation. (d) After the third location ligation.

instant time) changed with time by the rule of the down frequency modulation (FM). After the third location ligation, the center frequency changed with time by the rule of the up FM (Fig. 5(d)). There was no significant feature after the second location ligation (Fig. 5(c)). Their evolutionary spectral parameters can be seen in Table 2.

As shown in Table 2, the Q 's values of the evolutionary spectral quality number of the QRS-complex data of rabbit I after the first and second ligation basically remained at the mean value level of 0.813 (the maximum relative error

of Q 's values is equivalent to 5%). These data suggest that although there is a little change in the cardiac rhythm of rabbit I at this time, the cardiac system was still maintained in normal homeostasis. After the third location ligation, all of the high-frequency and low-frequency components of the evolutionary spectra significantly increased, while the Q 's values significantly decreased (the maximum relative error of Q 's values was more than 28%), and demonstrated an inner connection with the myocardial ischemia symptoms of the ECG waveforms indicated by the peaked

Table 2

Evolutionary spectral parameters of f_{cm} , f_L , f_H , W_b , and Q of the QRS-complex data chosen from different ECG data sets of rabbit I after the ligation.

	f_{cm} (Hz)	$(t_m - t_r)$ (s)	f_L (Hz)	f_H (Hz)	W_b (Hz)	Q
Mean value*	37.0		17.2	62.7	45.5	0.813
After the 1st ligation	31.0	0.0336 – 0.0294 = 0.0042	14.0	54.0	40.0	0.775
After the 2nd ligation	35.0	0.0471 – 0.0470 = 0.0001	17.0	60.0	43.0	0.814
After the 3rd ligation	34.0	0.0353 – 0.0362 = -0.0009	4.0	62.0	58.0	0.586

* Averaged value from after anesthesia and before the ligation.

T-wave in the time domain (Fig. 2(d)). The dropping of the Q 's values of the evolutionary spectra of the QRS-complex data suggests that the rhythm of the cardiac system is abnormal, and the ability of the cardiac system to maintain homeostasis is impaired, a serious marker of EPMI.

The segments of ECG data of rabbit II at different time intervals after the ligation can be seen in Fig. 6. As described above, only one location of the LADCA was ligated after anesthesia, and the ligation location was selected near the left main coronary artery. This model simulates a blood vessel stenosis which occurs at one location. The 12 ECG data sets were recorded at different time intervals. The QRS-complex data were randomly selected from these data, and their corresponding ESHPFSD figures can be seen in Fig. 7. When comparing Fig. 6 with Fig. 7 at 240 s after the ligation, the ST-segment of the ECG signals was depressed (Fig. 6(b)) and the main energy of the evolutionary spectra of the QRS-complex data was shifted to the lower frequency (Fig. 7(b)).

The low-frequency components (<17 Hz) of the QRS-complex data increased significantly at 660 s after the ligation (Fig. 6(c)), and the energy of the evolutionary spectra mainly concentrated in the low-frequency component (Fig. 7(c)). Further, at this time point the frequency peak, f_{cm} , of the evolutionary spectrum occurred at approximately 0 Hz, and the half-power points bandwidth of the evolutionary spectrum fell significantly. The evolutionary spectral parameters of the QRS-complex data can be seen in Table 3; these data were selected randomly from the 12 experimental data sets. As shown in Table 3, Q 's values of the evolutionary spectra of the QRS-complex data were basically maintained at the mean value level of 0.7849 before the ligation until 510 s after the ligation, suggesting that although the cardiac rhythm of rabbit II is changed, it still remains in a normal range. After approximately 660 s (datum set 6), the evolutionary spectral parameters of the QRS-complex data suddenly changed; i.e., as $f_{cm} \rightarrow 0$, $Q \rightarrow 0$, suggesting that the cardiac rhythm of rabbit II is abnormal, and that the cardiac system has lost the ability to maintain homeostasis.

4. Discussion

The evolutionary spectrum is 3D time-dependent, which is suitable for the singularity detection of power/frequency density distributions of the non-stationary signals at the instant time point in the time–frequency domain. In the present study, we proposed a new algorithm for estimating the evolutionary spectrum of ECG signals based on the wavelet transform. The instantaneous frequency spectra of the non-stationary signals could be detected from the evolutionary spectra, which suggested that the singularity information contained in the sudden signals of the living system, or even the instantaneous characteristics of transient signals such as earthquake data, can be further identified. The new algorithm could estimate the evolutionary spectra of the recorded experimental data. Thus, evolutionary spectral analysis can provide some heuristic information of the time–frequency domain for understanding the dynamical systems that produced the data. The examples used in the present study showed that if the continuous real mother wavelet was used to make the wavelet transform of non-stationary signals, then frequency-aliasing will occur in the corresponding evolutionary spectrum; however, the continuous complex mother wavelet can strongly reduce the frequency-aliasing. Moreover, under the condition in which the uncertainty principle in time–frequency domain, say $\Delta t \Delta f \geq 1/(4\pi)$, is satisfied, the instantaneous frequency spectrum of the R-wave and the dynamic frequency spectral distributions of the R-wave can be obtained by the evolutionary spectral analysis. The dynamic instantaneous frequency spectral distributions of the R-wave can not only reveal the non-stationary property and singularity of the ECG signals in the time domain, but also determine the singularity information contained in the Fourier transform of the ECG signals. The traditional Fourier transform analysis can only represent the overall frequency characteristics of the signals overall time, and the local singularity of the signals would affect the whole distribution characteristics of the frequency spectra. Further, it can barely identify

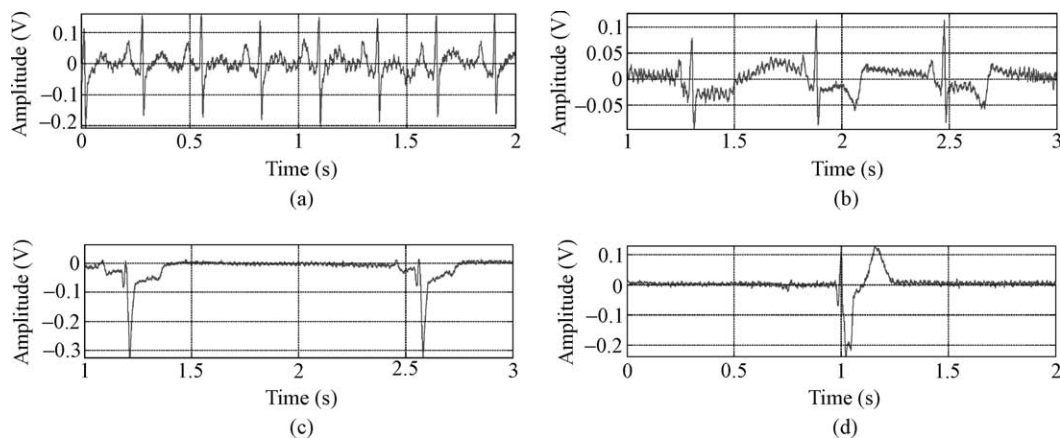


Fig. 6. The segments of ECG data of rabbit II at different time intervals after the ligation, and their Fourier transform frequency spectra. (a) At 60 s before the ligation. (b) At 240 s after the ligation, the ST-segment depression. (c) At 660 s after the ligation the small Q -wave occurs. (d) At 21 min after the ligation the upright T -wave is resumed.

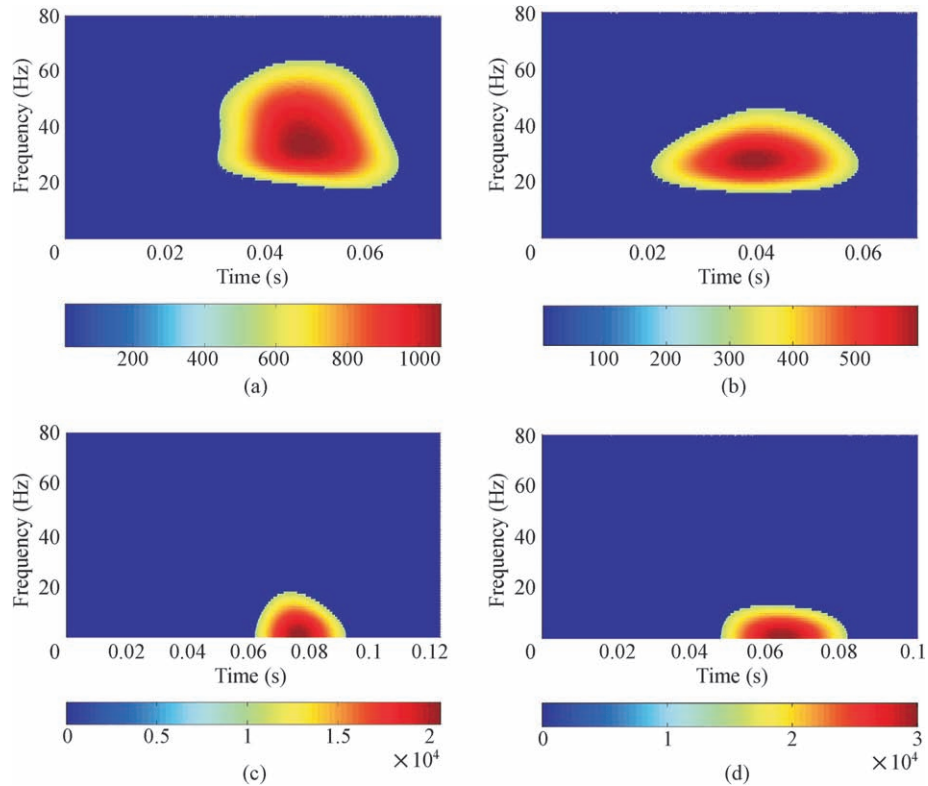


Fig. 7. ESHPSD of the QRS-complex data. These data were chosen randomly from the ECG of rabbit II at different time intervals after the ligation. (a) At 60 s before the ligation. (b) At 240 s after the ligation. (c) At 660 s after the ligation. (d) At 21 min after the ligation.

Table 3

Evolutionary spectral parameters of f_{cm} , f_L , f_H , W_b , and Q of the QRS-complex data chosen from the different ECG data sets of rabbit II after the ligation.

	f_{cm} (Hz)	$(t_m - t_r)$ (s)	f_L (Hz)	f_H (Hz)	W_b (Hz)	Q
MVBL*	32.8		16.7	58.5	41.8	0.7849
Datum set 2, 240 s after ligation	27.0	$0.0396 - 0.0401 = -0.0005$	16.0	45.0	29.0	0.9310
Datum set 3, 330 s after ligation	25.0	$0.0314 - 0.0271 = 0.0043$	12.0	41.0	29.0	0.8621
Datum set 4, 420 s after ligation	25.0	$0.0256 - 0.0244 = 0.0012$	12.0	43.0	31.0	0.8065
Datum set 5, 510 s after ligation	26.0	$0.0320 - 0.0301 = 0.0019$	9.0	45.0	36.0	0.7220
Datum set 6, 660 s after ligation	0.0	$0.0766 - 0.0551 = 0.0215$	0.0	17.0	17.0	0.0
Datum set 7, 750 s after ligation	0.0	$0.0710 - 0.0301 = 0.0409$	0.0	17.0	17.0	0.0
Datum set 8, 840 s after ligation	0.0	$0.0586 - 0.0311 = 0.0275$	0.0	15.0	15.0	0.0
Datum set 9, 930 s after ligation	0.0	$0.0529 - 0.0291 = 0.0238$	0.0	16.0	16.0	0.0
Datum set 10, 17 min after ligation	0.0	$0.0542 - 0.0301 = 0.0241$	0.0	16.0	16.0	0.0
Datum set 11, 19 min after ligation	0.0	$0.059 - 0.0301 = 0.0289$	0.0	13.0	13.0	0.0
Datum set 12, 21 min after ligation	0.0	$0.0645 - 0.0321 = 0.0324$	0.0	12.0	12.0	0.0

* Mean value before the ligation.

the accurate time of the existing singularity of the signals. The evolutionary spectral analysis method can overcome these problems.

The rabbit LADCA ligation experiments simulated changes in the physiology state of the EPMI. Myocardial ischemia resulting from left coronary artery stenoses is the major symptom of coronary heart diseases including acute myocardial infarction. The results of the evolutionary spectra of the QRS-complex data of the ECG signals selected randomly from the two different experiments demonstrated the following: (1) The experiments on rabbit I, where three

LADCA ligations were performed, simulated physiological changes derived from the multi-point stenoses of the blood vessels. Before the ligation, the Q 's values of the evolutionary spectral quality number of the QRS-complex data remain at approximately the mean value level, suggesting that when the peak frequency of f_{cm} is changing, the half-power points bandwidth of W_b changes at the same rate. This reflects a state where the normal cardiac system rhythms of the rabbits can maintain homeostasis, an indicator of the rhythm and non-stationary property of the normal ECG signals. After the third location ligation, all the high-frequency and the

low-frequency components of the evolutionary spectrum significantly increased; the Q 's values all fell significantly. There was a matched connection between these data and the myocardial ischemia of rabbit I, indicated by the peaked T-wave in the time waveforms of the ECG data. The homeostasis ability of the cardiac system was reduced, which is a serious indication of myocardial ischemia. (2) The experiments on rabbit II, where only one LADCA location was ligated, simulated the occurrence of single-location blood vessel stenosis. In these experiments, the electromagnetic field states of the cardiac system of rabbit II were changed after myocardial ischemia at different time points. Results showed that until 510 s after the ligation, the Q 's values of the evolutionary spectra of the QRS-complex data were basically maintained at their before ligation mean level of 0.7849, suggesting that although the cardiac rhythm of rabbit II was changed and the low-frequency components increased, it still remained in a normal range. At approximately 660 s after the ligation the evolutionary spectral parameters of the QRS-complex data suddenly changed (the peak frequency of $f_{cm} \rightarrow 0$ resulted in $Q \rightarrow 0$), suggesting that abnormal cardiac rhythms occurred in rabbit II and that the cardiac system had lost the ability to maintain homeostasis, a serious indication of myocardial ischemia. There was a matched connection between these data and changes of the signals of rabbit II in the time domain, with the ST-segment depression occurring first, followed by the small Q-wave, finally then the upright T-wave segment was resumed.

In summary, the results from the present study suggest that the evolutionary spectra quality number of the QRS-complex data can provide a novel medical diagnosis reference feature for identifying EPMI. As such, we suggest that from the view point of cardiac system dynamics, the quality number Q of evolutionary spectra of the QRS-complex data is the characteristic parameter of ECG in the time–frequency domain. There is a threshold value, for instance, a Q 's value greater than Q_t implies that the cardiac system is in homeostasis and heart behavior is normal, while a Q 's value less than Q_t implies that the cardiac system has lost homeostasis, a serious indicator of myocardial ischemia. Finally, whether the experimental results from the present study completely reflect the mechanism of myocardial ischemia in the human requires verification using the evolutionary spectrum analysis method to analyze further experimental and clinical data.

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