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A novel approach to phase space reconstruction of single lead ECG for QRS complex detection

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ABSTRACT

Two-dimensional reconstructed phase space (RPS) of single lead Electrocardiogram (ECG) is usually implemented by plotting the ECG amplitude $x(t+\tau)$ versus $x(t)$ into the two-dimensional coordinate system, where the value of time delay τ determined the morphology of the reconstructed trajectory. However, the value of τ is very difficult to select because different theories derived different τ. In this paper, a novel approach to phase space reconstruction of single lead ECG without using τ is proposed. The first two coordinates (x, y) from (x, y, t) were projected into the x-y coordinate system, where x is the amplitude of the ECG and y is the first order difference of x. Besides, time t is corresponding to the sampling time moment. As QRS complex is usually the most striking waveform that dominant with the highest amplitude or the highest slope, the largest semi-circle in the RPS is usually derived from QRS complex. The location of QRS complex in the original ECG is determined by the time coordinate t that corresponds to the largest semi-circle in the x-y coordinate system. The algorithm was developed at the MIT-BIH Arrhythmia Database (109494 beats within 24 h in total) and was tested on the Long-term ST Database (8897780 beats within 1991.8 h in total). The accuracy (ACC), the sensitivity (SEN) and the positive predictivity value (PPV) for the MIT-BIH Arrhythmia Database were 99.81%, 99.87% and 99.93%, respectively; while the corresponding values for the Long-term ST Database were 99.87%, 99.96% and 99.91%, respectively. Meanwhile, the consuming time was only 6.73 ms for processing 6 s' ECG data. Furthermore, the anti-noise ability of the proposed method was tested on the MIT-BIH Noise Stress Test Database (4265 beats in total at each noise level for one lead ECG). Both ACC and PPV were higher than 85% and the SEN was higher than 99% even when the signal-to-noise ratio (SNR) was as low as 0 dB. In conclusion, the proposed algorithm achieves better performance on QRS complex detection when in comparison with the state-of-the-art methods, and it is suited for the detection of QRS complex in the ECG associated with poor signal quality and severe arrhythmia.

1. Introduction

The body-surface Electrocardiogram (ECG) is the projection of the Vectorcardiogram (VCG) on a specific direction, such as leads V1, V2 and so on. It is a field distribution of the ECG on the human body from the cardiac source, which is affected not only by the ECG source, but also by the characteristics of the medium of the human body. Consequently, the one-dimensional body-surface ECG is actually a projection of the four-dimensional VCG $\boldsymbol{V} = (x, y, z, t)$ on a specific direction of the human body. According to the theory of time delay embedding [1], the reconstructed phase space (RPS) of the ECG in high-dimensional space may show some important features of the VCG, such as chaos, nonlinear feature and attractors in the constructed trajectory. For time delay embedding, the feature and the morphology of the reconstructed trajectory relies on two parameters, including the embedding dimension m and time delay τ.

The trajectories in the RPS contain information of heartbeat segmentation. Plesnik et al. [2] utilized the Euclidian distance in the phase space for fiducial-point detection, and achieved an accuracy of 64.86% for the MIT-BIH Noise Stress Test Database. Lee et al. [3] proposed a real-time algorithm of delay-coordinate mapping

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for QRS complex detection using the characteristics of the area in the RPS of the ECG, which achieved a detection rate of 99.58% for the MIT-BIH Arrhythmia Database. Cvikl et al. [4] modified the delay-coordinate mapping-based algorithm with a band-pass pre-filtering for QRS complex detection, which got a sensitivity of 99.82% and a positive predictivity of 99.82% for the MIT-BIH Arrhythmia Database and a sensitivity of 99.72% and a positive predictivity of 99.37% for the Long-term ST Database.

The RPS of the ECG is also used for diagnosis of ventricular arrhythmias. Koulaouzidis et al. [5] used a statistical index in the RPS (m = 8, τ=10) of the ECG (Fs = 125) for the detection of ventricular tachycardia (VT) and ventricular fibrillation (VF). Roopaei et al. [6] got an accuracy of 91.51% for distinguishing between normal sinus rhythm and ventricular fibrillation.

Moreover, Fang et al. [7] studied the single-lead ECG-based personal identification by delay-coordinate mapping and achieved accuracies of 96%, 95% and 96% from the mutual-nearest point distance, the normalized spatial correlation, and the mutual-nearest point match, respectively. Ayyoob [8] used features extracted from the RPS for detecting sleep apnea and got an accuracy of 94.8% over the Physionet sleep apnea dataset using a kernel-based SVM classifier.

Prior researchers studied ECG characteristics in the RPS by plotting x($t+\tau$) against x(t) into a two-dimensional coordinate system [2]. However, the selection of τ is not easy. In this paper, a new approach to ECG phase-space reconstruction without using τ is proposed. The novel method of ECG phase-space reconstruction is used for QRS complex detection. Firstly, QRS complex is enhanced by matched filtering. Subsequently, the RPS is constructed with the amplitude of the filtered ECG and its first order difference. Then the striking semi-circles are extracted from the RPS. After that, false-positive and false-negative detections are corrected according to RR intervals and semi-circle structures. Finally, QRS complex is located in the original ECG.

2. Theory

2.1. Delay coordinates mapping

A phase portrait of a dynamic system that described by one-dimensional time series {$x(k)$} can be reconstructed in a m-dimensional state space as formula (1) [1].

$$\mathrm{X}(k) = [x(k), x(k+\tau), \ldots, x(k+(\mathrm{m}-1)\tau)] \quad (1)$$

where k is the serial number of ECG sampling, m is the embedding dimension and τ is the time delay for m-dimensional state space $\boldsymbol{X}$.

Two-dimensional RPS of the ECG is usually implemented through the Takens method of delays [1], by plotting $x(t+\tau)$ versus $x(t)$ into a two-dimensional coordinate system. It is also called the delay coordinate mapping [2]. When index m is fixed, the morphology of the reconstructed trajectory is only determined by time delay τ. Each point in the phase portrait represents a specific state of the system at a specific time. However, different theories derived different τ, making the selection of τ quite difficult.

One two-dimensional image is actually a two-dimensional matrix. It is intuitive and easy to be drawn in one figure. Therefore, m is often chosen as 2 for the ECG. However, the value of τ is different from one study to another. Plesnik et al. [2] selected τ as one sampling point (Fs = 250, τ=4 ms) for fiducial point detection. Lee et al. [3] thought that the optimal mapping time delay was 20 ms for QRS complex detection. Roopaei et al. [6] used τ_1 = 10 ms and τ_2 = 40 ms to detect ventricular fibrillation.

2.2. New approach to phase-space reconstruction

A new approach without using τ to ECG phase-space reconstruction is proposed by projecting the first two indices of the three-dimensional coordinate (x, y, t) into the x-y coordinate system, where x is the amplitude of the ECG and y is the first order difference of x. Besides, time t is an invisible time parameter in the coordinate system. A phase portrait of a normal sinus ECG cycle followed by a premature ventricular contraction (PVC) is shown in Fig. 1. The amplitude x is shown in Fig. 1(c), and the first order difference y is shown in Fig. 1(a), while the phase coordinate system (x, y) is shown in Fig. 1(b).

For three-dimensional coordinate (x_k, y_k, t_k), only the first two coordinate (x_k, y_k) is projected into the x-y two-dimensional map, while the third index t_k is not projected onto it. When one coordinate (x_k, y_k) is detected as the fiducial point for QRS complex, the third parameter time t_k indicates the position of QRS complex. Therefore, the third parameter time t_k is an indispensable index to locate the position of QRS complex.

The largest semi-circle in the RPS is usually corresponding to QRS complex, because QRS complex is usually the most striking waveform than other feature waves. Therefore, the position of QRS complex in the original ECG is determined according to the time coordinate t that associated with the largest semi-circle in the RPS. For the normal heartbeat in Fig. 1(c), 6 points {A, B, C, D, E, F} are marked, where the huge semi-circle B-C-D is derived from the top part of the first QRS complex. For the PVC heartbeat in Fig. 1(c), 5 points {G, H, I, J, K} are marked, where the huge semi-circle G-H-I-J is derived from the top part of the second QRS complex.

The positive points in Fig. 1(c) are associated with the points on the right side of zero point in x-coordinate of Fig. 1(b), such as points {A, B, C, D, E}. Similarly, positive points in Fig. 1(a) are associated with the points on the top side of zero point in y-coordinate of Fig. 1(b), such as points {A, B, G}. As points I and J in Fig. 1 (c) are in the downtrend cure of QRS complex, they are positive in x-coordinate but negative in y-coordinate in Fig. 1 (b). The fiducial point for heartbeat segmentation is the local maxima or minima in QRS complex. Therefore, point C in the right side of the semi-circle B-C-D and point H in the right side of the semi-circle G-H-I-J in Fig. 1 (b) can be regarded as the fiducial points for the normal heartbeat and the PVC heartbeat, respectively. When automatic segmentation of semi-circles that corresponded to QRS complex is made, QRS complex on the ECG is located.

One advantage of such visualization is the simultaneous presentation of the amplitude and the first order difference of the complete ECG record. Moreover, the sampling time sequence is also kept in the x-y coordinate system. For example, the orders of A- B- C- D- E- F- G- H- I- J- K in Fig. 1 (a, c) are also kept in Fig. 1 (b). The time parameter t is the x-coordinate in Fig. 1 (a, c). However, it is a hidden variable in Fig. 1 (b). On the basis of three-dimensional coordinate (x, y, t), the information on the amplitude, the change rate of the amplitude, and the signal sampling order are all recorded in the phase portrait.

Another advantage of such visualization is the alignment-free for heartbeat clustering [7]. It avoids the detection of ECG characteristic points to align the period signal of ECG cycles. ECG waveform will cluster by self-similarity of phase space trajectory without using time-align parameter.

2.3. Comparison between delay coordinate mapping and the proposed approach

Although a few researchers have used the RPS for the ECG feature point detection, they are all focused on the delay coordinate mapping. Both Lee et al. [3] and Cvikl et al. [4] used the area of QRS complex as the main feature for QRS detection, while Plesnik et al.