An Optimized Automatic P Wave Delineation Method Based on Phasor Transform

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Abstract

Accurate P wave detection is important for arrhythmia diagnosis, e.g. P wave absence or P duration for atrial fibrillation diagnosis and other atrial arrhythmias. Phasor transform is an effective method for ECG fiducial points delineation. It maps each ECG sample into a phasor to enhance slight variations and preserves morphology and magnitude characteristics. In this paper, we optimized the automatic P wave delineation method based on phasor transform in four aspects, i.e., signal denoising, wave localization, candidate points detection, and optimal points selection. In our experiments, the length of the search window and the degree of phasor transform were established through various trials. Especially, along with zero-crossing points of the phasor signal, intersections of the phasor signal and the original ECG signal are obtained as candidates, which make the most contribution to delineation results. For validation, the QT Database with 3194 P wave annotations from 105 records of two leads is adopted. As a result, we reached F1 scores of 94.67% and 93.56% with detection error rates (DERs) of 10.80% and 13.06% for P wave onset and offset points detection, respectively. The F1 score and DER for P peak detection under a tolerance of 75 ms were 95.33% and 9.46%, respectively, which outperforms other reproducible works and their combinations.

1. Introduction

For many years, electrocardiogram (ECG) signals have been widely used for the diagnosis of heart diseases due to their rich and useful clinical information. Precise detection of multiple ECG characteristic points e.g., the onset and offset of the P wave, QRS complex, and T wave, is a difficult task with great challenges, especially for P waves because of their small amplitudes, diverse shapes, and unclear feature points.

A lot of methods have been studied in the field of P wave detection for decades. A common way of thinking is to combine the signal amplitude, the first derivative, and even the second derivative of ECG for P wave detection [1]. These kind of methods are easy to implement, however, they are usually not suitable for P waves with large variations and could be easily affected by noise. Therefore, some methods like the low pass differentiation technique [2] are introduced, and others apply pattern recognition [3] to deal with the waveform variation issue. Still, these methods are sensitive to noise and are not accurate enough for clinical use.

On the other hand, methods proposed in [4-7] locate the QRS complex first, and then detect P and T waves by setting appropriate thresholds based on the QRS complex. However, these methods depend greatly on the accuracy of the QRS complex detection, which leads to performance loss in ECG signals with ectopic beats, sometimes even computationally expensive [8]. Meanwhile, with the development of computer science and technology, machine learning based methods play a more and more important role in the field of ECG diagnosis. Studies in [9-11] used machine learning techniques such as support vector machine, K-nearest neighbour, and regression tree to realize accurate P wave detections. Machine learning methods also have limitations, such as requiring fine-designed artificial features and well-labelled datasets.

As phasor transform based P wave detection method proposed in [12-14] provides a new idea for P wave detection, we propose an optimized automatic P wave delineation method based on phasor transform. We construct three cascaded filters for noise reduction and adopt the adjacent U and J points in assistance of P region localization. The phasor transform method is utilized and moreover, zero crossing of the phasor signals together with its intersection of the original ECG are considered as potential fiducial points. Finally, an optimal selection strategy for candidate fiducial points is applied throughout the whole process for the improvement of the delineation. The QT database [15] with 3194 P wave annotations is utilized for evaluation. We achieved F1 scores of 94.67%, 93.56%, and 95.33%, with detection error rates (DERs) of 10.80%, 13.06%, and 9.46% for P wave onset, offset, and peak detection, respectively.

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2. Method

The proposed method contains the following steps: 1) denoise signals by a median filter and three cascaded filters with cut-off frequency from 0.67-35 Hz; 2) locate the P wave region roughly according to adjacent R complexes and their RR intervals; 3) apply the phasor transform; 4) find P peak candidates and their corresponding fiducial points through synthesis method; 5) use optimization strategy for final delineation. The block diagram of our method is shown in Figure 1.

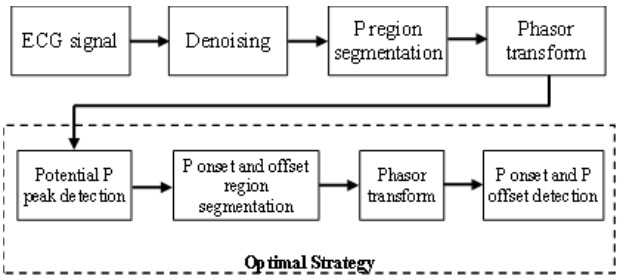

Figure 1. The block diagram of the proposed method

2.1. Preprocessing

In order to remove baseline wandering, power-line interference, and electromyography noise, a median filter is applied and three digital filters using the kaiser window, i.e., a low pass filter with 35 Hz cut-off frequency, a high pass filter with 0.67 Hz cut-off frequency, and similarly a notch filter of 50 Hz, are built in Matlab and cascaded. The order of filters is set to 65, and the window length and beta are set to 65 and 4.538, respectively.

2.2. Phasor Transform

Phasor transform easily transfers a sinusoidal function from the time domain into the complex number domain [16]. Martínez et al. [12] applied phasor transform on ECG signals for automatic delineation of ECG fiducial points. The ECG signal is transferred into phasor $y[n]$ as follows:

$$y[n] = R_v + jx[n], \qquad n = 1,2,\dots,N \tag{1}$$

where R_v is a constant value that is used as the real component of the phasor, and $x[n]$ is the original ECG signal in time domain which is regarded as the imaginary component. Two hyper-parameters of this phasor are computed as follows:

$$\varphi[n] = tan^{-1}\left(\frac{x[n]}{R_v}\right) \tag{2}$$

$$M[n] = \sqrt{R_v^2 + x[n]^2} \tag{3}$$

Here, $\varphi[n]$ stands for phase, which retains the morphology information of the original ECG， and $M[n]$ preserves the magnitude information for each original sample. In this work, phasor transform is applied to provoke the slight variations in P waves in the original time domain, which provides a basis for potential P fiducial points detection.

2.3. P Wave Delineation

The P regions are firstly located in accordance with QRS complexes. Specifically, the i^{th} P region is between the J points of the preceding QRS complex, i.e., $J(i-1)$, and the U points of the succeeding QRS complex, i.e., $U(i)$, where the U point and the J point indicate the start and the end of the QRS complex, respectively. We further shrink this area to $J(i-1) + 0.7 \times RR(i)$ to $U(i)$, where $RR(i)$ is the RR interval for the i^{th} heartbeat, as shown in Figure 2. After median and moving average filtering, this region is then transferred into the complex domain by phasor transform with R_v set to 0.003, and the $\varphi[n]$ and the $M[n]$ of each ECG sample are retained correspondingly.

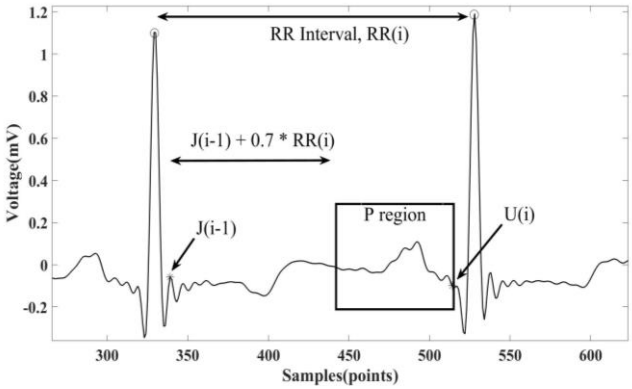

Figure 2. An example of P region segmentation

The local maximum of $\varphi[n]$ and $-\varphi[n]$ are listed in descending sequence and their corresponding samples in the original time domain are marked as potential P peaks. A search window of length 15 is further applied in order to remove potential peaks that are too close to the edge of the region. Figure 3 denotes all potential P peaks on both the original signal and the phasor signal.

Except for candidates that are too close to the P region boundary, the onset and offset points delineation is applied to all peak candidates. Take the first optimal candidate as an example, a search window of length 20 is placed forward and backward respectively to demarcate the onset and the offset region of the P wave. Similarly, these regions are filtered by a median filter and are transferred into φ_{onset} and φ_{offset} series by phasor transform with R_v set to 0.005.

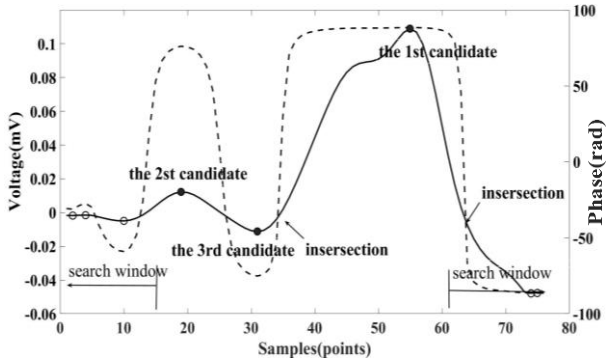

Figure 3. Examples of potential P peaks, the solid line stands for original ECG, and the dotted line represents the phasor signal. Circles that are blackened are preferred candidates while others are deleted by a search window.

Then, the end of the P onset region is narrowed to the position where the maximum first-order difference of φ_{onset} lies while the begin of the P offset region is adjusted to where the minimum first-order difference of φ_{offset} lies. And the location of zero crossing points that are close to those derivative extremes are marked as candidates of onset and offset points, denoted by $pon_{zero-crossing}$ and $poff_{zero-crossing}$. In addition, the intersection of the original ECG series and the transferred series are adopted as other candidates of onset and off set points, denoted by $pon_{intersection}$ and $poff_{intersection}$. Figure 4 shows an example of these intersection points.

Finally, an optimal fiducial points selecting strategy is adopted as follows. The P onset points and the P offset points are located in the middle between the zero crossing points and the intersection points when both candidates exit. Otherwise, the detected candidate is obtained directly as final delineation results.

3. Database

In this paper, the QT database [15] is adopted for P wave delineation evaluation. The QT database is derived from 7 different databases with 105 two-lead ECG records of 250 Hz sampling rate. The last 5 minutes of these records are manually annotated by cardiologists, including the onset, peak, and offset of P waves. In total, 3194 fiducial P points are identified which provides a standard for P wave delineation evaluation in the following part.

4. Results

The method proposed above is evaluated on QT database and a sample deviation of 75 ms equivalent is adopted based on AAMI ECAR recommendations [17]. Table 1 shows the results summary for P peak, P onset and P offset detection on both leads from the QT database.

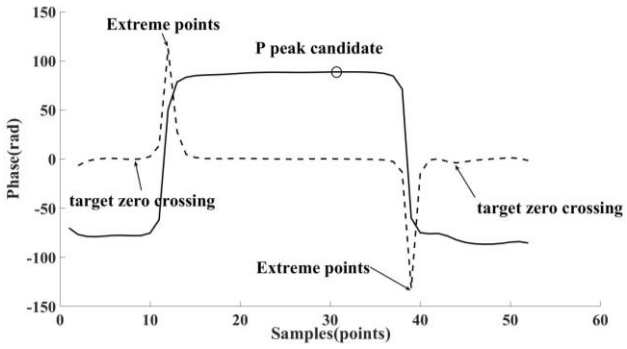

Figure 4. An example of zero crossing detection. The solid line stands for the transformed P region signal while the dotted line represents its first-order difference series.

Table 1. Performance Summary for P Wave Delineation

Points	TP	FP	FN	F1 (%)	DER (%)
peak	5466	343	192	95.33	9.46
onset	5427	380	231	94.67	10.80
offset	5364	445	294	93.56	13.06

For comparison to other works, we reproduced the phasor transform based method in [18] on QT database and evaluated P peak detection results. The F1 scores for [18] are 89.41% and 85.74%, with DERs of 21.20% and 28.65% on lead I and lead II, respectively. And our F1 scores are 95.24% and 95.43%, with DERs of 9.65% and 9.26% on lead I and lead II respectively, which outperforms greatly to the results above. Ablation experiments are further conducted to prove the contribution of the intersection candidates and optimal strategy, the results are shown in Table 2.

Table 2. Performance Summary for Ablation Experiment

Experiment	Points	TP	FP	FN	F1 (%)	DER (%)
No peak candidate optimization	peak	4562	1222	1097	79.73	40.98
	onset	4467	1311	1194	78.10	44.25
	offset	5237	569	421	91.36	17.50
PT with zero crossing	peak	5438	371	220	94.85	10.45
	onset	5388	418	270	94.00	12.16
	offset	5316	493	342	92.72	14.76
PT with intersection	peak	5466	343	192	95.33	9.46
	onset	5234	572	424	91.31	17.60
	offset	5339	470	319	93.12	13.94

We could see that the proposed potential peak points detection method together with the optimal selection

method makes a great contribution to the final result, especially to the P peak and P onset detection. Moreover, onset and offset fiducial points denoted directly by zero crossing or by intersection are attempted. And all results of both trials are no better than the proposed one, which indicates the achievement of the optimal fiducial points selecting strategy.

5. Conclusion

In this paper, we proposed a method based on phasor transform for P wave delineation and developed it with a new fiducial candidate detection method and an optimal selection strategy. The experimental results above prove that these attempts contribute to the increase of the detection scores greatly. In the future, we will construct our own P wave database, develop and verify the proposed method on it.

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