A Wavelet-Based ECG Delineation with Improved P Wave Offset Detection Accuracy

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In this paper, we present an improved version of ECG delineation approach based on the continuous wavelet transform and singlescale approach. The algorithm was design to detect five main ECG significant points, which are QRS onset, QRS offset, T wave offset, P wave onset and P wave offset. The introduced approach was evaluated on the standard CSE multilead database. The obtained delineation results are comparable with other methods and accomplished given database criteria. The implemented algorithm improvement significantly increases accuracy of the P wave offset detection, which was the problematic part of the previous version of this method.

1 Introduction

The correct and accurate delineation of electrocardiogram (ECG) is very important to a cardiac disease diagnosis. The first and the most important part of ECG signal analysis is the correct detection of QRS complexes. The QRS complex is the most easier waveform to detect, but the highest possible detection accuracy is needed. Once QRS complexes positions are found, detection of T waves and P waves can follow.

In this paper, we present an improved version of ECG delineation approach, which was originally introduced in [7]. The implemented improvement significantly increases accuracy of the P wave offset detection.

2 Methods

The presented ECG delineation approach is based on the continuous form of wavelet transform (CWT). The wavelet transform at different scales describes the time characteristic of a signal in different frequency bands. While dyadic wavelet transform (DWT) is restricted to scales, that are powers of two (used in [4]), CWT can be evaluated in any real positive scale. Using CWT, instead of DWT, provides us more possibilities. By selecting optimal scale, we can minimize the influence of noise, artifacts and baseline drift.

The CWT of a time-continuous signal *x(t)* is defined by the integral

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

where $\psi(t)$ is the wavelet function (mother wavelet), a is the scale parameter and b is the translation parameter.

We tested several prototype wavelets to find the optimal wavelet for ECG delineation. Authors in [4] used quadratic spline function and authors in [5] used Gaussian smoothing function. We achieved best results with biorthogonal wavelet *bior1.5*. Another difference lies in the chosen scale approach. Authors in [4] used multiscale approach for finding similarities across several dyadic scales. Our approach is using only one optimal scale for each ECG waveform. The scale 15 is used for detection of QRS onset and QRS offset. This scale however is not optimal for detection of other three ECG significant points. The scale 41 was found as the optimal scale for T offset, P onset and P offset detection. The scales 15 and 41 provides best delineation results on ECG signals sampled by 500 *Hz* sampling frequency. The wavelet *bior1.5* at scales 15 and 41 is shown in Fig 1.

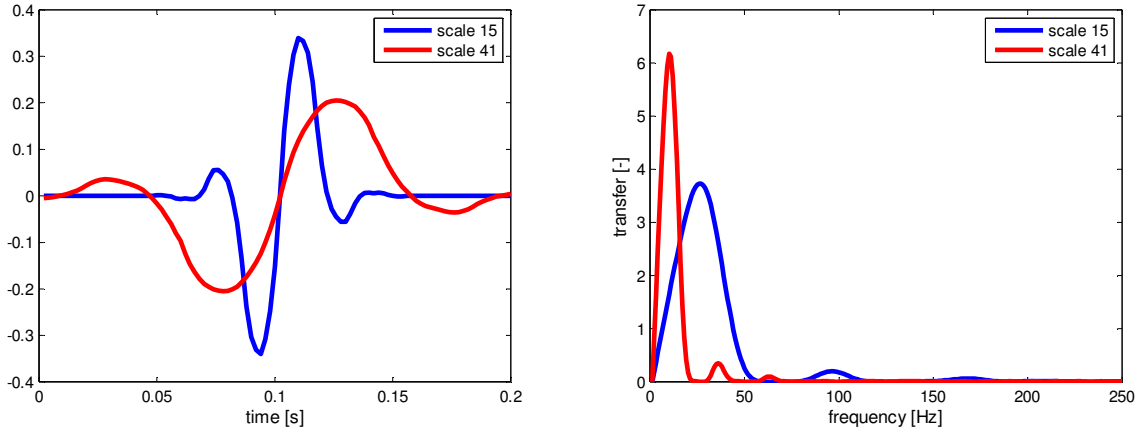

Fig 1. Wavelet *bior1.5* (left) and its magnitude spectra (right) at scales 15 and 41.

Regarding the selected prototype wavelet, zero-crossings of the CWT correspond to the local maxima of the signal modulus and the local maxima of CWT modulus correspond to maximum slopes in the signal. In the first step, the algorithm searches for pairs of modulus maxima exceeding threshold ξ_{QRS} in the scale 15. The QRS positions are detected as a zero-crossings between the pairs maximum-minimum, or minimum-maximum. Then, positions of QRS onset and QRS offset are detected using thresholds ξ_{QRSon} and $\xi_{QRSoffset}$. Positions of T waves, P waves and their boundaries are detected using similar approach in the scale 41. The example of delineation of one ECG cycle is shown in Fig 2.

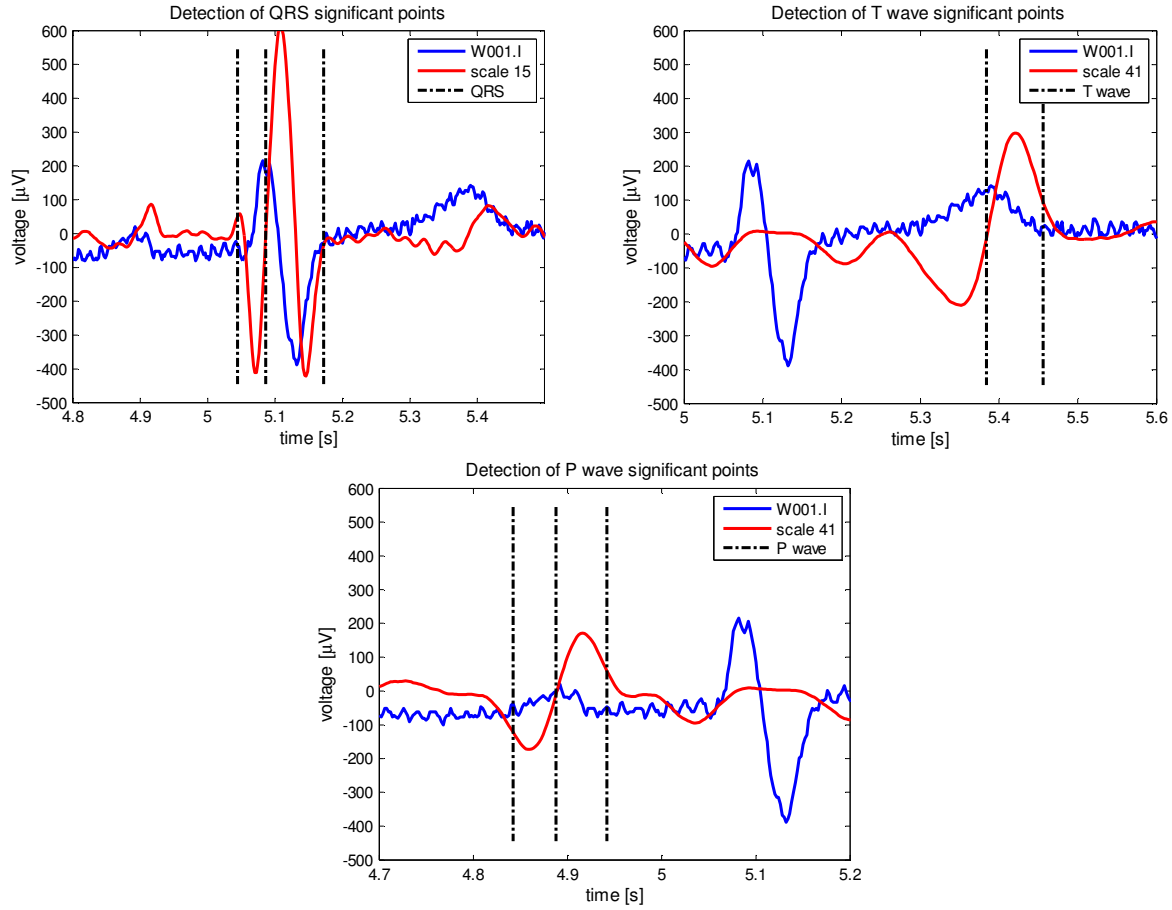

Fig 2. Delineation of one ECG cycle (signal W001.I).

The most problematic part of this approach (introduced in [7]) was the accuracy of the P wave offset detection. This is caused by the influence of adjacent QRS complex in the scale 41. In order to suppress this influence we improved our algorithm in the following way. After QRS onset and QRS offset are detected in the scale 15, the QRS complex is eliminated by using linear interpolation between the QRS onset and QRS offset positions. In such a signal, only T waves and P waves remains. The scale 41 is calculated from this modified signal and P wave offset positions are no longer influenced by adjacent QRS complexes. The example of QRS elimination approach by using linear interpolation is shown in Fig 3.

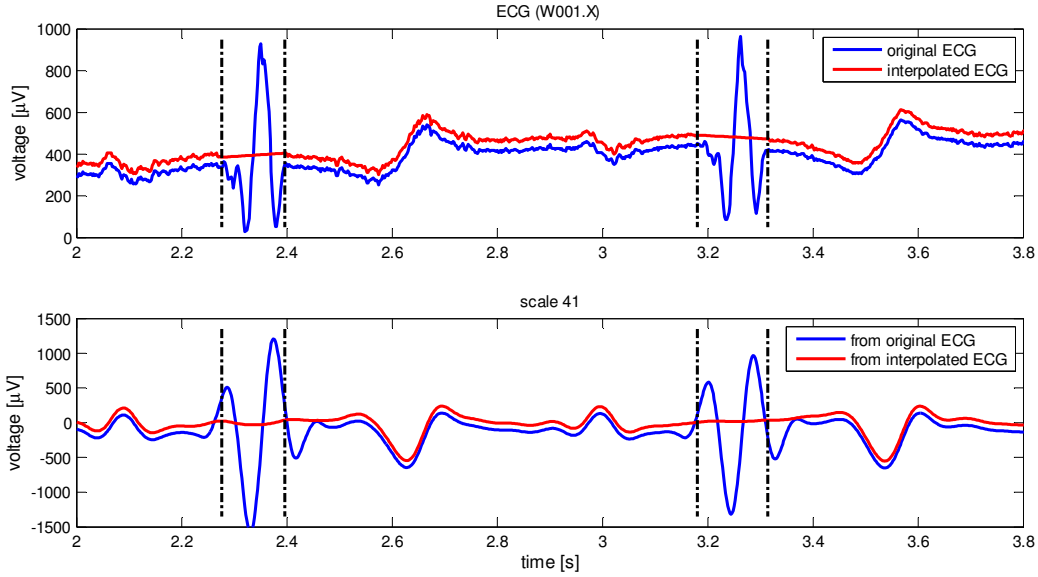

Fig 3. Elimination of QRS complex by using linear interpolation.

The example of delineation of three ECG cycles is shown in Fig 4.

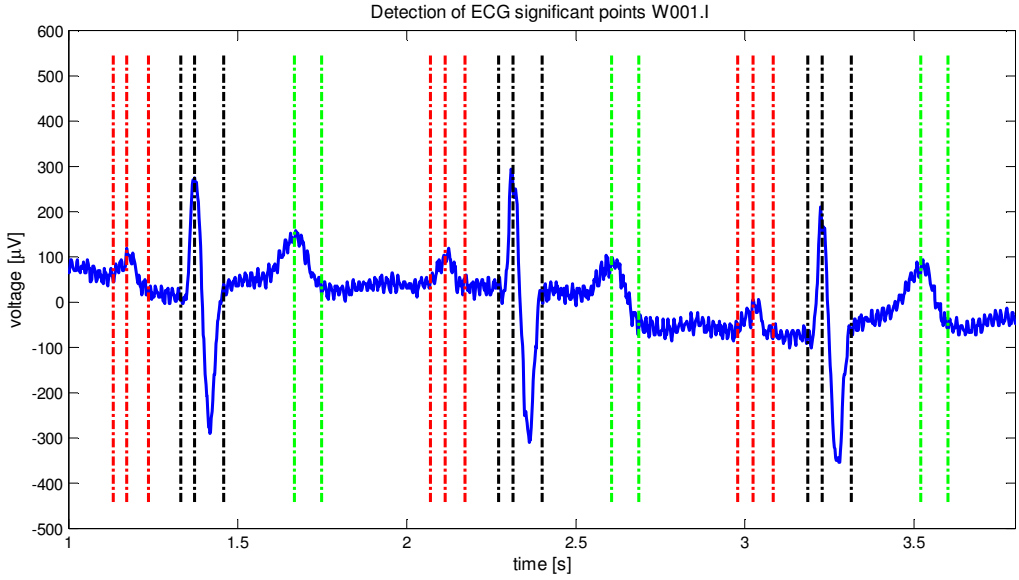

Fig 4. Delineation of three ECG cycles (signal W001.I).

3 Results

The proposed improved ECG delineator was evaluated on standard CSE multilead measurement database (CSEDB). The CSEDB contains of 125 ECG signals sampled by 500 *Hz* sampling frequency and each signal includes 12 standard leads and orthogonal Frank leads. Designed algorithm was evaluated separately on standard leads and on Frank leads, using the same set of program parameters.

The CSEDB is annotated database, containing reference positions of five ECG significant points. These reference positions are available only for one heart cycle in each ECG signal and are common for all 15 leads. Our algorithm process each lead separately, thus is necessary to assess the global positions for comparison with the CSEDB. Each global value is gained as one of the individual positions, by using special selection algorithm. This algorithm uses sorting and sliding window approach.

To assess proposed QRS, T and P wave detector, we calculated the sensitivity *Se* given by the equation

$$Se = TP/(TP + FN), \tag{2}$$

where *TP* is the number of true positive detections and *FN* is the number of false negative detections. The calculated sensitivities *Se* are given in Tab 1.

Tab 1. Detection results on the CSE database.

Leads	Sensitivity of QRS detection	Sensitivity of T wave detection	Sensitivity of P wave detection
Standard leads	99.19 %	98.36 %	98.17 %
Frank leads	99.13 %	97.37 %	97.09 %

The delineation results achieved in [7] and by improved algorithm presented in this work are given in Tab 2,

Tab 2. Delineation results on the CSE database.

Significant point	Stand. leads m ± s (ms) (algorithm [7])	Stand. leads m ± s (ms) (this work)	Frank leads m ± s (ms) (algorithm [7])	Frank leads m ± s (ms) (this work)	Tolerances $2s_{CSE}$ (ms)
QRS onset	0.4 ± 4.0	0.3 ± 4.0	1.5 ± 4.4	1.3 ± 4.6	6.5
QRS offset	-0.2 ± 5.0	0.8 ± 4.7	2.5 ± 6.7	2.0 ± 5.6	11.6
T offset	0.5 ± 12.2	-2.2 ± 12.2	0.9 ± 19.7	-5.6 ± 19.1	30.6
P onset	1.1 ± 5.9	1.4 ± 6.1	-1.5 ± 10.4	-3.3 ± 7.9	10.2
P offset	2.0 ± 13.5	1.2 ± 6.1	0.4 ± 16.9	3.1 ± 14.5	12.7

where *m* is the mean deviation between the program results and database annotations, *s* is the standard deviation and $2s_{CSE}$ are delineation error tolerances given for CSE database in [6].

While the values of standard deviations are very important for programs comparison and evaluation, the more detailed results in a form of histograms are shown in Fig 5.

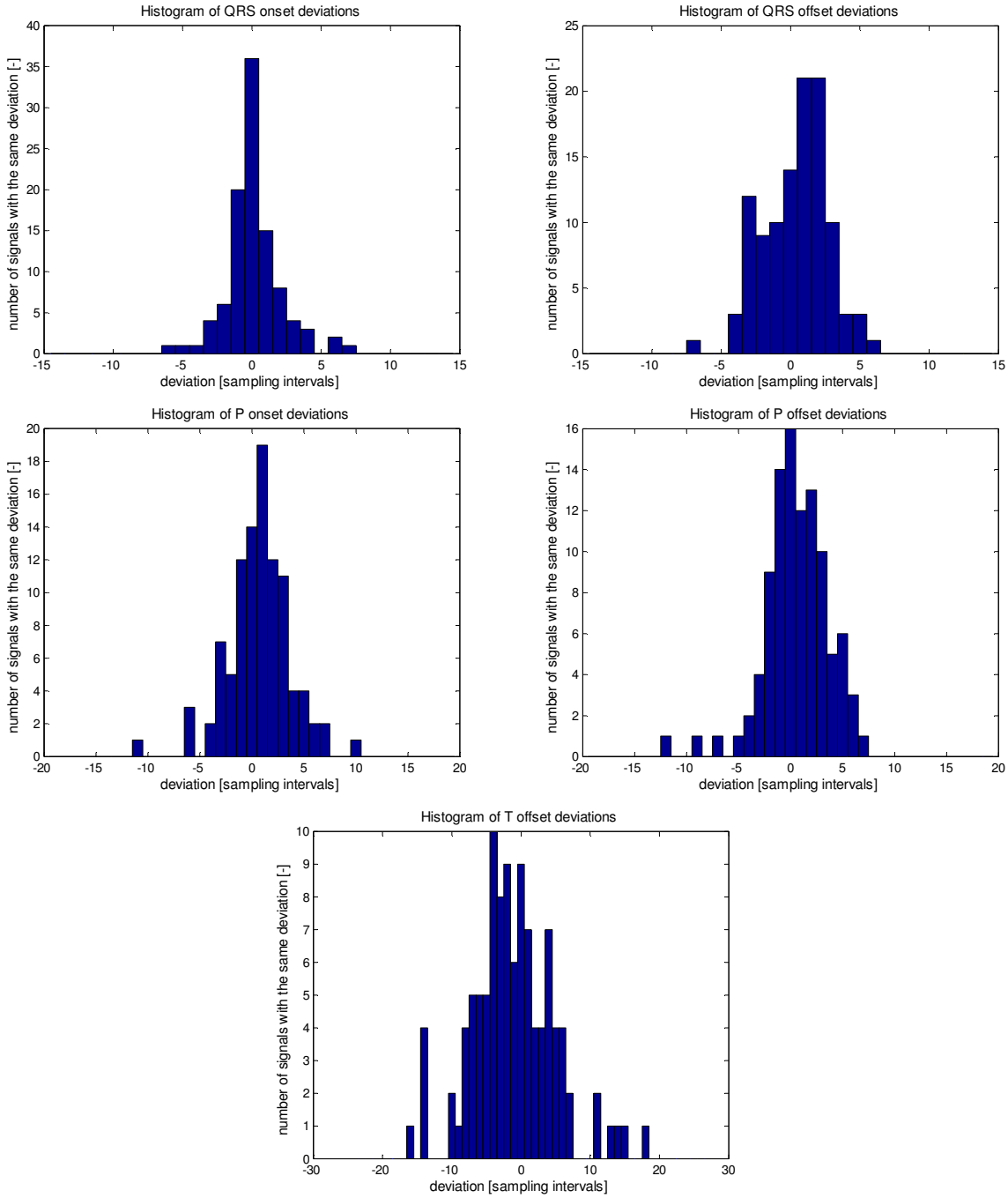

Fig 5. Histograms of deviations between program results and database annotations for 12 standard leads.

4 Discussion

The CSE Working Party provided delineation criteria for CSEDB in a form of two standard deviations $2s_{CSE}$ [6]. Some authors [4], [5] considered, that an algorithm should accomplish $s < 2s_{CSE}$ (the loose criterion), while some others considered, that $s < s_{CSE}$ should be accomplished (the strict criterion). We compared our delineation results with both criteria.

The improved ECG delineator accomplished the loose criterion for all significant points on 12 standard leads and for all points except P offset on Frank leads. The strict criterion was accomplished for QRS offset, T offset and P offset on 12 standard leads. The results achieved by other methods tested on the CSEDB are shown in Tab 3,

Tab 3. Delineation results of other methods on the CSE database.

Method	QRS onset m ± s (ms)	QRS offset m ± s (ms)	T offset m ± s (ms)	P onset m ± s (ms)	P offset m ± s (ms)
Martínez [4]	1.3 ± 6.3	5.8 ± 10.9	1.3 ± 21.8	-4.9 ± 5.4	-1.0 ± 6.4
Laguna [3]	-2.1 ± 7.4	-0.2 ± 3.6	2.6 ± 10.5	1.0 ± 7.9	-1.0 ± 5.1
De Chazal [2]	0.9 ± 3.6	-0.6 ± 7.1	N/R	N/R	N/R
Sahambi [5]	N/R ± 2.0	N/R ± 4.0	N/R ± 20.0	N/R ± 4.0	N/R ± 6.0
Chouhan [1]	-7.5 ± 6.6	0.9 ± 9.2	-18.5 ± 14.4	3.2 ± 9.2	9.4 ± 27.6

where N/R stands for Not Reported.

The proposed improved delineator achieved results comparable with methods mentioned in Tab 3. Especially standard deviations for 12 standard leads are extremely low. In comparison with the previous version of algorithm [7], the significant improvement of P offset detection accuracy was achieved by elimination of QRS complexes, before the scale 41 is calculated.

5 Conclusions

The designed delineation method did well in comparison with database criteria and other delineation approaches. The problematic part of our algorithm, the P offset detection accuracy, was successfully improved. The delineator is strong especially on 12 standard leads, but can be used with Frank leads too. The algorithm itself is extremely fast and simple, because of used singlescale approach. It appears to be robust and effective tool for fast and accurate delineation of ECG databases or long ECG recordings.

Acknowledgement

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