Delineation of QRS-complex, P and T-wave in 12-lead ECG

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Summary
An accurate and efficient method of detection and delineation of QRS-complexes, P-waves and T-waves in 12-lead ECG is presented in this paper. The delineation process is completely automatic and is based on detections done on the basis of adaptive quantized threshold of the QRS and non-QRS feature signal. The feature extraction is done using a modified definition of slope of the ECG signal. Due to the inclusion of slope and threshold, of ECG and feature signal respectively, the filtering of the raw ECG signal for noise removal and baseline drift removal become pre-requisite. The delineation performance of the proposed algorithm is validated using original ECG recordings from the dataset-3 of the CSE multi-lead measurement library. The delineation results obtained clearly indicate a high degree of agreement with the manual annotations done by the referees of CSE dataset-3.

Key words:
ECG, QRS-complex, P-wave, T-wave, ECG delineation.

1. Introduction

The detection and delineation of ECG waves is important in automatic cardiac disease diagnosis. In a clinical setting, such as intensive care units, it is essential for automated systems to accurately detect and classify ECG wave components such as QRS-complex, P-wave and T-wave. Identifying characteristics points of 12-lead ECG by computers is crucial in the development of computer aided ECG interpreters, which are necessary for 12-lead ECG instruments as recommended by American College of Physicians and American Heart Association [1].

The identification of QRS-complexes forms the basis for almost all automated ECG analysis algorithms. The presented algorithm [2] employs a modified definition of slope, of ECG signal, as the feature for detection of QRS-complexes. A sequence of transformations of the filtered and baseline drift corrected ECG signal is used for extraction of a new modified slope-feature. Two feature-components are combined to derive the final QRS-feature signal. Multiple quantized amplitude thresholds are employed for distinguishing QRS-complexes from non-QRS regions of the ECG waveform. An adequate amplitude threshold is automatically selected by the presented algorithm for the detection and delineation the QRS-complexes. A QRS detection rate of 98.56% with false positive and false negative percentage of 0.82% and 1.44% has been reported.

Detection of P and T-waves is an important part in the analysis and interpretation of ECG. The presented algorithm [3] detects and delineates both P and T-waves simultaneously. It employs a modified definition of slope, of ECG signal, as the feature for detection of ECG wave components. A number of transformations of the filtered and baseline drift corrected ECG signal are used for the extraction of this new modified slope-feature. Five feature-components are combined to derive the final feature signal. Amplitude threshold of the final feature signal is employed for distinguishing P and T waves with respect to already detected QRS-complexes. P-wave detection rate of 96.95% with false positive and false negative percentage of 2.62% and 3.01% has been reported. Similarly, T-wave detection rate of 98.01% with false positive and false negative percentage of 3.08% and 1.93% has been reported.

Delineation performance of the algorithm is validated by calculating the mean and standard deviation of the differences between automatic and manual annotations by the referee cardiologists and reported in the present paper. The on-sets and off-sets of the detected QRS-complexes, P and T-waves are found to be within the tolerance limits given in CSE library.

2. Pre-processing

2.1 Filtering

Simple Moving Averages algorithm is used to filter the random noise in the raw ECG signal. Various window sizes, for moving averages, from 5 to 15 have been attempted for obtaining a convincing level of smoothness.

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Good results were available with window sizes ranging from 8 to 14. However, to uniformly cover all the cases of the database a window size of 11 was found the most suitable and hence implemented. The roughness due to excessive noise in a few cases was not removed in single attempt; in such cases, a second iteration provides excellent results. For the purpose of automation and uniformity, all the cases are filtered with two iterations. The filtered ECG signal is then rendered for removal of the baseline drift.

2.2 Baseline Drift Removal

A three-step procedure is used to remove baseline drift of the signal as explained below:
(i) The trend of the filtered ECG signal is estimated and represented graphically by a contour. The contour passes through the filtered signal and represents its trend with respect to the zero-line; (ii) discrepancy between the contour and the zero-line is measured and eliminated by vertically shifting each sample of the filtered signal; and (iii) the samples of the contour-corrected signal are then shifted vertically by its overall median value.

A significant reduction in the baseline drift is attained after the contour-correction and the median correction. In most of the cases, no more correction is needed, but in a few cases a further correction in the beat-to beat interval is required. After the QRS-detection, the baseline correction may be implemented in the beat-interval (RR-interval) and a drift-free signal may be attained as described by Chouhan and Mehta [4].

3. QRS-Delineation

The delineation of QRS-complexes is accomplished by demarcating their boundaries from its onset to offset by a rectangular marking pulse:

1. Extract QRS-feature signal F_Q defined for each of the 5000 sample values of the ECG signal and normalize it by dividing it with the maximum value [2].
2. Demarcate those portions of F_Q with QRS-candidate marking pulses C_Q, which exceed 5% of the normalized peak magnitude of F_Q:

$$C_Q(n) = \begin{cases} 1, & \text{if } F_Q(n) > 0.05 \\ 0, & \text{otherwise} \end{cases}$$

$$n = 1, 2, \ldots, 5000 \qquad \ldots (1)$$

The CSE ECG library containing ECGs of 10 seconds duration sampled at 500 Hz thus giving 5000 samples for each ECG record.

Define a range of normalized adaptive amplitude-thresholds [2] and by taking one threshold at a time, testify the crossing of the threshold by the peak value of F_Q within all the QRS-candidate marking pulses C_Q in the entire sampling duration from 1^{st} to 5000^{th} sampling instants.

3. Demarcate detected QRS-complexes D_Q for all the 12 leads of a given case, count and list the number of D_Q, that is, number of QRS-detections and compute statistical properties for these numbers of detections for the case [2].
4. Select all the QRS-detections, demarcated by QRS-detection marking pulses D_Q of the given case with [2]:

(a) Minimum value of standard deviation
(b) The corresponding value of median equal to the correct and reliable number of QRS-complexes in that case, evaluated by algorithm [2]
(c) Demarcate the first column out of these QRS detections (Table 1) [2] with QRS Marking Pulses MP_Q. That is, the first out of multiple correct QRS detections demarcated by D_Q are declared as the *final QRS-detection* and the corresponding marking pulses are designated as MP_Q.
(d) These final QRS marking pulses MP_Q delineate the QRS-complexes in the given ECG signal. The portions of the ECG signal within these marking pulses MP_Q are the detected QRS complexes with the presented algorithm.

4. Delineation of P and T-waves

The delineation of QRS complexes is accomplished by demarcating their boundaries from its onset to offset by a rectangular marking pulse:

1. Extract non-QRS feature signal F_{NQ} defined for each of the 5000 sample values of the ECG signal and normalize it by dividing it with the maximum value.
2. Demarcate all the ECG signal portions with non-QRS candidate marking pulses C_{NQ}, which exceed 5% of the normalized peak magnitude of F_{NQ}.
3. Identify and demarcate P-waves and T-wave out of candidates $C_{NQ}(n)$ with respect to each of the already detected QRS-complexes as reference using the rule-base detailed by Chouhan and Mehta [3]
4. The Marking Pulse MP_P completely demarcates P-waves of the ECG signal. The beginning of this pulse indicates the P onset and the end of this pulse indicates the P offset.
5. The Marking pulse MP_T completely demarcates P-waves of the ECG signal. The beginning of this pulse

indicates the T-onset and the end of this pulse indicates the T-offset.

5. Delineation Results

The validation of the proposed algorithm for QRS-complex, P and T-wave detection and delineation is done using 125, simultaneously recorded, 12-lead ECG records of dataset 3 of CSE multi-lead measurement library [5]. As a result of an international cooperative project entitled, "Common Standards for Quantitative Electrocardiography," (CSE), an ECG reference database has been established. This library has been developed to standardize and evaluate the performance of computer-derived ECG measurement programs. The dataset 3 consists of 125 original 12-lead ECG recordings covering a wide variety of cardiac abnormalities such as incomplete right bundle branch block, complete right bundle branch block, left anterior fascicular block, complete left bundle branch block, acute myocardial infraction, anterior myocardial infraction, postero-diafragmatic myocardial infraction, lateral or high-lateral myocardial infraction, apical myocardial infraction, myocardial infraction+ intraventricular, conduction defect, left ventricular hypertrophy, right ventricular hypertrophy, pulmonary emphysema, ischemic ST-T changes, bigeminy, trigeminy, multiple PVC's, multiple APC's, supraventricular tachycardia, atrial flutter, atrial fibrillation, 1st AV-block, 2nd AV-block, Wolf-Parkinson-white syndrome, pace-maker, etc. Every record picked from CSE ECG database is of 10 sec duration sampled at 500 samples per second thus giving 5000 samples in all. Out of the 125 ECG records, only 25 ECG records were analyzed by a group of five referee cardiologists. Attention was focused on the exact determination of the onsets and offsets of P, QRS and T-waves. The referee's results are available in the CSE library and are used to calculate the mean and standard deviation. The algorithm has been implemented using *MATLAB*.

Fig. 1 shows (a) the filtered and baseline drift corrected ECG signal S (b) QRS complexes delineated by marking pulses MP_Q superimposed over signal S (c) non-QRS feature signal F_{NQ} and non-QRS candidates C_{NQ} shown as rectangular pulses, and (d) Rectangular non-QRS marking pulses MP_{NQ}, delineating P and T waves, superimposed over signal.

The error in milliseconds (ms) between the manually annotated onsets and offsets of the ECG components by the CSE referee and the corresponding values obtained by the proposed algorithm are listed in Table 1.

Fig. 2 shows delineation performance of the algorithm for 25 refereed cases of CSE dataset-3 plotted in the deviation range of m±2s.

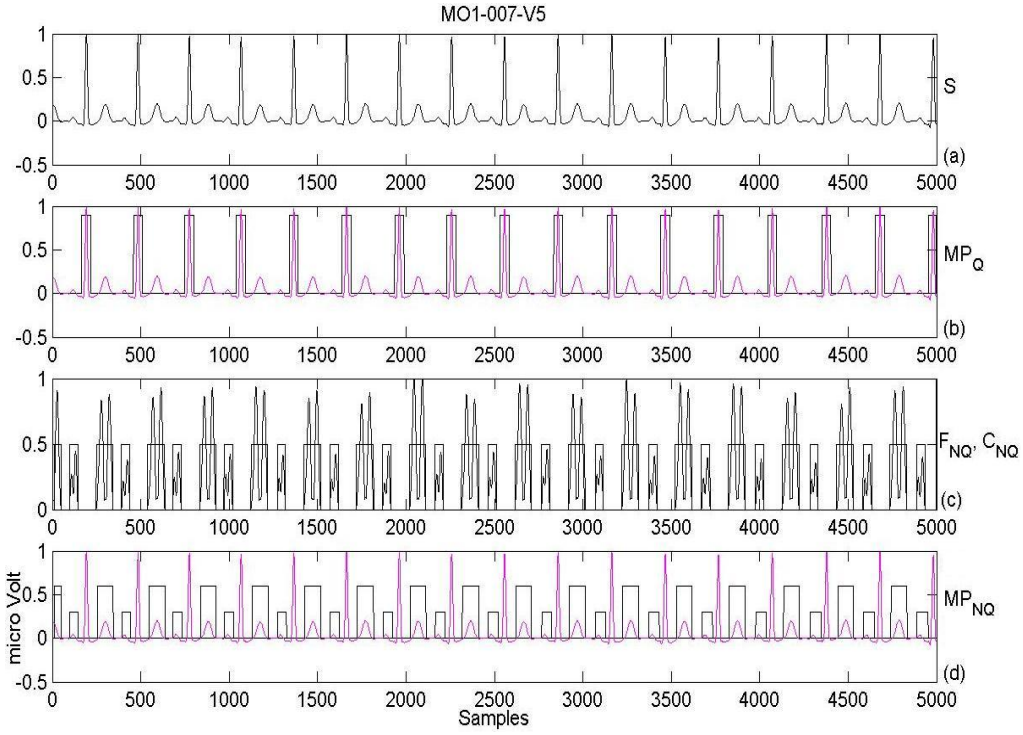

Fig. 1(a) ECG signal S (b) Already demarcated QRS marking pulses MP_Q superimposed over signal S (c) Final non-QRS feature signal F_{NQ} and non-QRS candidates C_{NQ} shown as rectangular pulses (d) Rectangular non-QRS marking pulses MP_{NQ}, delineating P and T waves, superimposed over signal S

Table 1 Case-wise error in ms for the 25 refereed cases of CSE dataset-3

Sr. No.	Case Number	P-onset (ms)	P-offset (ms)	QRS-onset (ms)	QRS-offset (ms)	T-offset (ms)
1	MO1_001	26	0	-4	4	-24
2	MO1_006	-4	-4	-16	0	-30
3	MO1_011	4	8	-6	2	0
4	MO1_016	-4	2	-12	8	-4
5	MO1_021	-2	0	-12	6	12
6	MO1_026	2	12	2	4	-20
7	MO1_031	12	10	-14	-2	-22
8	MO1_036	-4	6	0	-14	-18
9	MO1_041	-8	12	-12	-24	-4
10	MO1_046	-4	2	-4	12	-42
11	MO1_051	2	8	-8	6	-32
12	MO1_056	0	18	-8	2	-14
13	MO1_061	18	-28	2	-2	-32
14	MO1_066	0	8	-4	2	-16
15	MO1_071	18	14	-8	2	-12
16	MO1_076	8	-4	4	-8	-2
17	MO1_081	-14	-2	-6	8	-18
18	MO1_086	-4	2	-6	16	-32
19	MO1_091	2	18	-4	-8	-40
20	MO1_096	4	8	-10	-10	-34
21	MO1_101	4	-2	-12	10	-30
22	MO1_106	-6	2	-6	6	4
23	MO1_111	6	134	-28	-6	-32
24	MO1_116	14	14	-10	14	-6
25	MO1_121	10	-4	-6	-6	-14

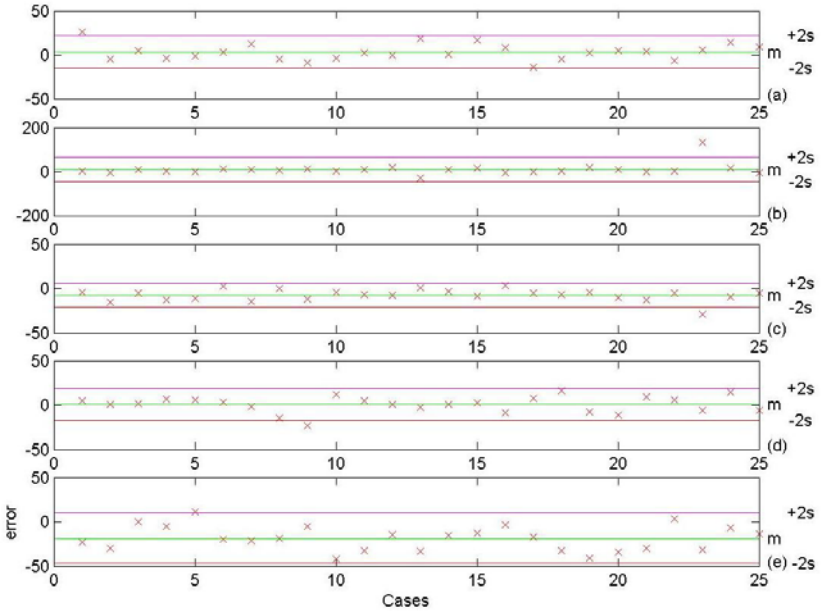

Fig. 2 Delineation performance of the algorithm for 25 refereed cases of CSE dataset-3 plotted in the deviation range of m±2s for : (a) P onset (b) P offset (c) QRS onset (d) QRS offset (e) T offset; m=mean of error in ms, s= standard deviation of error in ms with respect to referee results

The delineation results of the proposed algorithm are displayed in Table 2. In the last column of the Table 2, the accepted two-standard deviation ($2s_{CSE}$) tolerances as recommended by the CSE working party [4], are given. The delineation performance shows that standard deviation of the errors obtained with the proposed algorithm is well within the tolerance limits. The algorithm presented in this paper successfully delineates a wide variety of P-wave, QRS complex and T-wave morphologies.

Table 2 Comparison of the delineation results with the referee's annotations

Parameter	Mean (ms)	Standard deviation (ms)	Tolerences ($2s_{CSE}$) (ms)
P-on	3.2	9.2	10.2
P-off	9.4	27.6	12.7
QRS-on	-7.5	6.6	6.5
QRS-off	0.9	9.2	11.6
T-end	-18.5	14.4	30.6

6. Conclusion

This paper presents a new method for component wave detection in 12-lead ECG signal. The method has been exhaustively tested using the CSE ECG dataset-3 covering a wide variety of QRS-complexes, P and T-wave morphologies. It not only detects the component waves of the ECG, but also delineates them accurately. A significant detection rate is obtained. The proposed method accurately detects normal, inverted and biphasic P and T-waves. The delineation results show that the standard deviations of the errors are within the tolerance limits. The information obtained by this method is very useful for ECG classification and cardiac diagnosis. This information can also serve as an input to a system that allows automatic cardiac diagnosis.

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