Adaptive Technique for P and T Wave Delineation in Electrocardiogram Signals

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Abstract— **The T and P waves of electrocardiogram signals are excellent indicators in the analysis and interpretation of cardiac arrhythmia. As such, the need to address and develop an accurate delineation technique for the detection of these waves is necessary. In this paper, we present a novel robust and adaptive T and P wave delineation method for real-time analysis and nonstandard ECG morphologies. The proposed method is based on ECG signal filtering, value estimation of different fiducial points, applying backward and forward search windows as well as adaptive thresholds. Simulations and evaluations prove the accuracy of the proposed technique in comparison to those proposed techniques in the literature. The mean error for the T peak, T offset, P peak and P offset values are found to be 9.8, 2.3, 7.3 and 3.5 milliseconds, respectively, based on the Physionet QT database, rendering our algorithm as an excellent candidate for ECG signal analysis.**

I. INTRODUCTION

The electrical activity of the heart is presented by the Electrocardiogram (ECG) signal. Due to the ease of use and noninvasiveness, ECG is not only used as a prime tool to monitor the functionality of the heart but also to diagnose the cardiac arrhythmia by extracting information about intervals, amplitudes, and wave morphologies of the different P, QRS, and T waves [1]. The extracted features from the ECG signal play an essential role in diagnosing many cardiac diseases. Hence, the development of a real-time accurate delineation method is of major importance for the research community especially for abnormal ECG signals. The delineation of T and P waves is more challenging because of their low Signal to Noise ratio (SNR). Various T and P -wave delineation methods have been proposed in the literature with different accuracy, methodology, sensitivity, and predictivity. In [2], a delineation technique based on digital signal processing is proposed. Using time curve derivative and adaptive threshold and taking into consideration the mean of the high frequency noise, this technique was able to delineate P and T wave with an accuracy of 99% on a data-size of 125 recordings. However, the size of the search window is fixed to heuristically values which makes it not suitable for real-time application. Similarly, [3] and [4] have used low-pass filter and adaptive search window but have not highlighted the detection of the various T wave morphologies which increases the false detection rate. Other types of filters have been also used such as the matched filter and was put forth in [5]. Other delineation techniques are based on analyzing the ECG signal in different time windows. Cuiwei Li *et al*. were the first to use Wavelet Transform (WT) in detecting ECG characteristic points throughout the multi-scale features of WT [6], and others have adapted the method with slight modifications [7],[8]. Discrete Fourier Transform and Discrete Cosine Transform are another set of transforms that have been used in the literature to delineate T and P wave [9],[10]. Delineation methods based on the concept of machine learning, classification, and pattern recognition are demonstrated in [11],[12]. These techniques provide a powerful syntactic approach but with insufficient delineation accuracy compared to the other methods.

In this paper, we introduce an adaptive T and P wave delineation technique which takes into account different waveform morphologies of T and P waves. By using an adaptive size of search window along with adaptive threshold, this method accurately detect peak, onset, and offset locations of T and P wave in each heartbeat. The remaining part of the paper is organized as follows. Section II presents the pre-processing stage of the raw ECG signal. In Section III, the different elements of T and P -wave proposed delineation method are described. The obtained results as well as a comparison with other algorithms are reported in Section IV. Finally, conclusions are stated in Section V.

A. ECG pre-processing

In the proposed method, the delineation of T and P -wave requires first the detection of QRS complex. This is done using the algorithm proposed by Pan and Tompkins (PAT) which consists of filtering, differentiating, squaring, and averaging of the ECG signal [13]. In each heartbeat, the QRS complex is used as a reference for the detection of T and P -wave in which two regions are demarcated with respect to the RR interval and QRS complex fiducial points. These regions are then used to form the forward and backward search window of the T and P waves respectively. Usually, the ECG signal is contaminated with both high and low frequency noise components which have greater impact on T and P wave due to their low amplitude. Thus, an important step is to remove the noisy components of the ECG

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signal which can be performed by filters. Since detecting the T and P waves require low noise ECG, the filtered signal from the PAT is used to process the T and P -wave. The filtering used by Pan and Tompkins algorithm is found to be satisfactory for our delineation and the resulted filtered signal is used for data representation to perform ECG delineation task. Differentiation and squaring in the PAT are utilized to enhance the QRS complex and the R peaks are detected from the last squaring stage.

II. T AND P -WAVE DELINEATION METHOD

The proposed delineation technique is performed in time domain and transformation such as Wavelet is not required. Once the search window and thresholds are defined, the T and P waves are delineated in a single step. The technique described in [7] requires multiple iterations if the T and P waves are not identified in the first step. The general flowchart of the delineation method is shown in Fig.1.

A. *T wave delineation*

T wave is the representation of repolarization of ventricles whereby the myocardium is prepared for the next cycle of the ECG. In the automatic delineation of the ECG by locating the onset and offset of different waveforms, the most important of these measurements is the detection of T wave ends, particularly T offset. The detection of the T offset is the most difficult among the ECG fiducial points, mainly due to the slow transition of the signal near the end of T wave. In addition, T waves have oscillatory patterns that vary from one individual to another which make the delineation process even more challenging.

1) T wave search window :

An infallible detection of T waveform and its fiducial points (e.g. T onset, T peak, and T offset) search window define the search space in the entitled signal. The boundaries of the search window are set to be adaptive and relative to the position of QRS offset and RR interval as shown in Fig.2. The forward search window contains the T wave boundaries, extended from the QRS offset to two-third of previous RR interval. A small segment after the QRS offset is excluded from the search window. This is due to the fact that T wave does not exist immediately after QRS offset but it occurs after a small segment known as the ST segment.

2) Adaptive threshold estimation :

The position of T peak is registered by finding either the local maximum or/and the local minimum in the entitled ECG signal within the search window (Tw1). The threshold is calculated using the previous T and R peak level values as shown below:

$$T_{wave_{th}} = \frac{T_{peak}}{R_{peak}} t_{thresh_{in}} \quad (1)$$

where $t_{thresh_{in}}$ is set between 0.1 to 0.2 based on the most recent detected values in the last 4 seconds. Adaptation to ECG wave morphologies would be improved by taking longer duration particularly in T peak and T offset. However, the algorithm targets real-time implementations and by increasing the adaptation interval more than 4 seconds a bigger

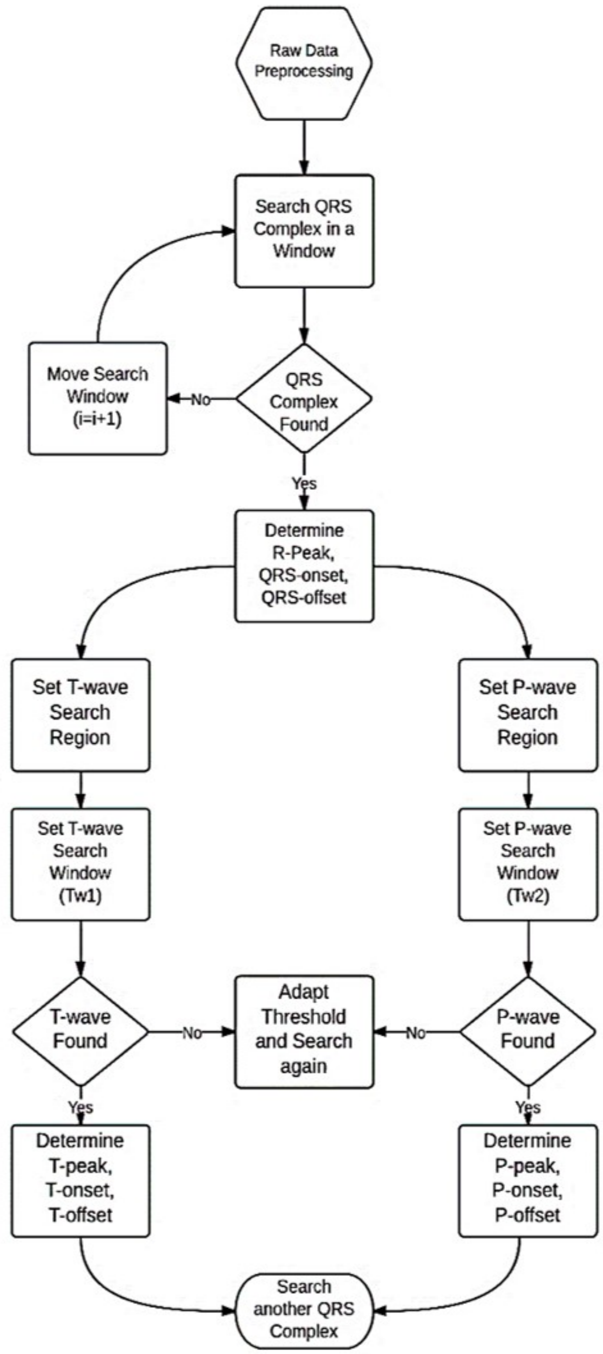

Fig. 1. Flowchart of T and P -wave delineation method

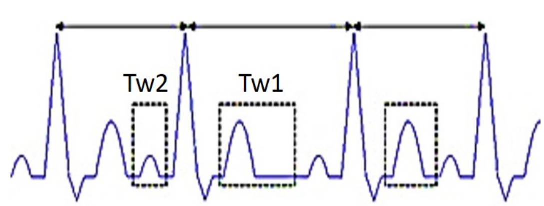

Fig. 2. Forward and Backward search window for T and P -waves

memory element is required. After multiple iterations, a 4 seconds interval is found to be enough and satisfactory.

The threshold is used to classify the morphology of the T wave present in each heartbeat. If the maximum point exceeds the threshold and the absolute value of the minimum point does not, then the T wave is recognized as a positive monophasic and the maximum point is registered as T peak. For a negative monophasic T wave, the absolute minimum value must meet the above requirement. In case of a biphasic T wave, both the local maximum and the absolute value of the local minimum should be greater than the threshold. Equations (2), (3), and (4) present the classification method of the T wave.

$$\begin{aligned} &T_{peak} = max\ \ (ecg_{filtered}\ \ (QRS_{onset} : Tw1)\ \ ) \\ &T_{peak} >\ \ T_{wave_{th}} \\ &T_{peak} value = T_{peak} \end{aligned} \tag{2}$$

$$\begin{aligned} &T_{peak} = min\ \ (ecg_{filtered}\ \ (QRS_{onset} : Tw1)\ \ ) \\ &abs\ \ (T_{peak}) >\ \ T_{wave_{th}} \\ &T_{peak} value = T_{peak} \end{aligned} \tag{3}$$

$$\begin{aligned} &T_{peak1} = max\ \ (ecg_{filtered}\ \ (QRS_{onset} : Tw1)) \\ &T_{peak1} >\ \ T_{wave_{th}} \\ &T_{peak2} = min\ \ (ecg_{filtered}\ \ (QRS_{onset} : Tw1)) \\ &abs(T_{peak2}) >\ \ T_{wave_{th}} \\ &T_{peak} value = T_{peak1}\ \ and\ \ T_{peak2} \end{aligned} \tag{4}$$

If T wave is not detected in the first trial, the threshold is reduced by half and the search method is repeated again till a T peak is detected. Furthermore, the proposed algorithm traces the onset and offset T values by finding the sample corresponding to the zero slope of the entitled ECG signal. The sample point which has a zero slope and former to T peak is identified as T onset. Similarly, T offset is determined at a further distance of T peak.

B. P wave delineation

P wave is the representation of repolarization of atrial and the proposed technique of P wave delineation is fairly similar to T wave delineation but with a backward adaptive search window (Tw2), as shown in Fig. 2. The search window is defined to be prior to QRS complex and the size is selected relative to QRS onset and extended to one-third of previous RR interval where the beat is usually begin. Another adaptive threshold is defined to detect P peak which is given in (5).

$$P_{wave_{th}} = \frac{P_{peak}}{R_{peak}} p_{thresh_{in}} \tag{5}$$

where $p_{thresh_{in}}$ is set between 0.1 to 0.2 based on the most recent detected values in the last 4 seconds. The algorithm detects the different P waveform morphologies, missing P wave, P onset, and P offset using the same approach discussed earlier in T wave delineation.

TABLE I
MEAN AND STANDARD DEVIATION OF THE PROPOSED DELINEATOR AND LITERATURE REVIEW

Method	Parameter	T_{peak}	T_{off}	P_{peak}	P_{off}
[2]	μ ms	NA	6.1	NA	4.4
	σ ms	NA	11.2	NA	6.29
[7]	μ ms	0.2	-1.6	3.6	1.9
	σ ms	13.9	18.1	13.2	12.8
[15]	μ ms	NA	8.3	NA	12.8
	σ ms	NA	12.4	NA	13.2
[16]	μ ms	-7.2	13.5	4.8	-0.1
	σ ms	14.3	27	10.6	12.3
This work	μ ms	9.8	2.3	7.3	3.5
	σ ms	4.8	9.8	10.3	7.8

III. RESULTS

The performance of the proposed T and P wave delineator is evaluated on QT Physionet database [14]. The experiment is conducted on single-lead ECG recordings which are taken from the Physionet QT database to reflect the real-world variability. The following two subsections highlight the delineation of different wave morphologies and report the analytical results respectively.

A. T and P -wave Delineation for different waveform morphologies

The delineation method is adapted with monophasic and biphasic wave morphologies which is a key factor to have an accurate and successful delineation of T and Pwaves. The threshold is adjusted based on the previous detected values of T or P and R amplitudes in the last 4 seconds. Fig.3 provides representative results on the delineation of T and P waves respectively. It is clear that the algorithm has successfully identified the T and P wave fiducial points within the designated search windows in each heartbeat. In addition, the different waveform morphologies whether it is inverted wave, non-inverted wave, or biphasic wave are accurately detected (Fig.3).

B. Analytical results

The delineation results on the QTDB show that the proposed technique is highly sensitive to T and P waves. The performance of the delineator is measured on mean error μ and standard deviation σ of the differences between the annotated and automated results. The mean errors for T peak, T offset, P peak and P offset are around the annotated values by 9.8, 4.8 and 9.8 milliseconds respectively, with corresponding standard deviation absolute values of 7.3, 3.5, 10.3 and 7.8 ms, respectively. A comparison with other published techniques from the technical literature is summarized in Table 1. The performance of the proposed method is found to be highly accurate and satisfactory as compared to other published results.

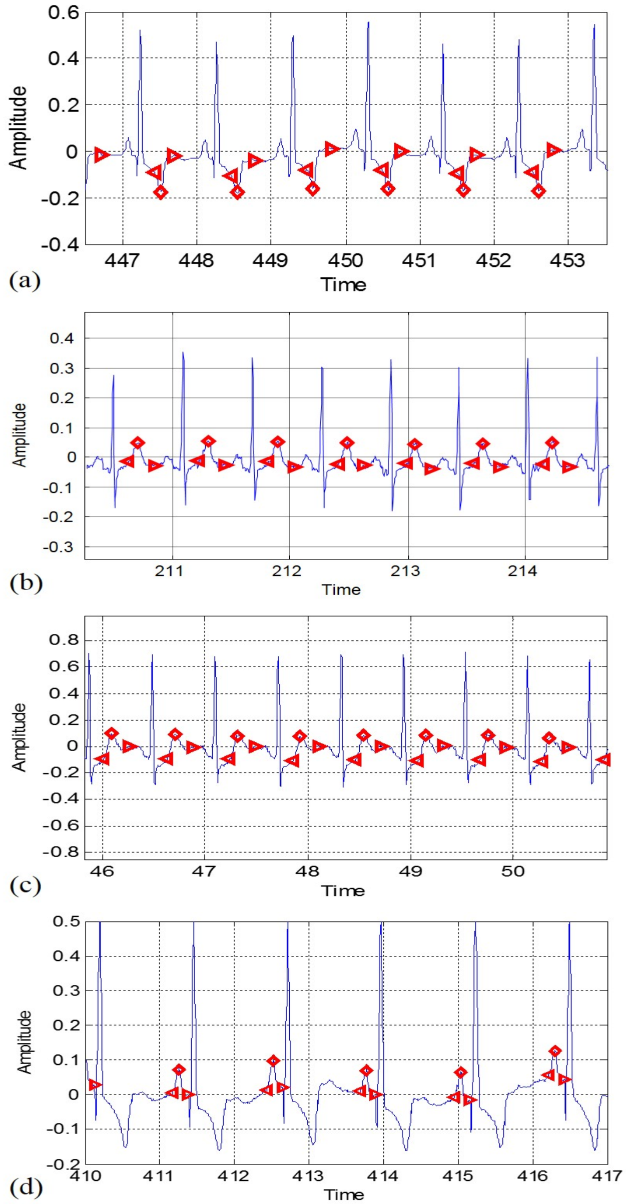

Fig. 3. Delineation of (a) Inverted T wave, (b) Non-inverted T wave, (c) Biphasic T wave, (d) Non-inverted P wave

IV. Conclusions

In this paper, an efficient and accurate technique to estimate the T- and P- wave delineation is presented. The technique is robust and adaptive for different waveform morphologies. In addition to the simplicity of this new technique, it is very suitable to real-time analysis, avoiding any complex operations required by the available similar delineation algorithms. Intensive test scenarios for the various ECG signal morphologies proved the accuracy of this technique, with a plenty of possible promising applications in ECG related research topics.

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