AN EFFICIENT AND ROBUST TECHNIQUE OF T WAVE DELINEATION IN ELECTROCARDIOGRAM

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Abstract: This study presented an efficient and robust method for the automatic delineation of T wave in the single-lead electrocardiogram. The method attained optimum performance using the fusion of delineation results obtained from a pair of new approaches. The first approach utilizes the advantage of time derivative and determines T wave ends using derivative curve analysis. The effect of local noise on the ECG signal is seized using a non-derivative approach which performs T wave delineation using the analysis of its waveform curvature toward the ends. Using the assumption that beginning and end of T wave exhibit the convex shape, this approach determines minimum radius of curvature of the convex regions at both ends. It is formally shown that the time instance corresponding to minimum radius of curvature coincides with T wave ends. The delineation results obtained from both the approaches are fused to achieve the optimum performance. The delineator attained a detection sensitivity of 99.9%, positive predictivity of 99.1% and an accuracy of 99.01% over the first lead of physionet QT database (20 records of 1, 000 beats each). The delineation errors are found well within the referenced intercardiologist observations, especially for T wave end. The mean error and standard deviation are found smaller than 10 *ms* which outperformed in comparison to other published results.

1 INTRODUCTION

The Electrocardiogram (ECG) is the record of time-varying bio-electric potential generated by the electrical activity of the heart. ECG provides an easiest way to monitor the functional activity of the heart without using of an invasive method. It is a prima tool used by the cardiologists in diagnosis of cardiac arrhythmia. In the automatic analysis of ECG, locating the beginning (onset) and end (offset) fiducials of its characteristic waveforms, the most difficult one among these measurements is the delineation of T wave. T wave is the representation of repolarization of ventricles whereby the myocardium is prepared for the next cycle of ECG. In the automatic delineation of T wave, the detection of its offset fiducial is more cumbersome due to rapid change of the signal near to its end. Furthermore, the end of T wave also concerns the irregularity causing in the electrical activity of the heart. The patterns of cardiac impulses responsible for T wave generation has been identified using the different methods available in the literature.

The information of time derivative has been utilized for the automatic detection of T wave end fiducials in the multilead ECG signals (Laguna et al., 1994). A similar method based on wavelet transform has taken the advantage of numerical differentiation and its robustness to the waveform variations (Li et al., 1995). The disadvantage of this method is its sensitivity towards the noise. In order to limit the noise-sensitivity, smoothing filters are used. Among the other methods of T wave delineation, one of them has consisted to the computation of an indicator related to the area covered by T wave curve (Zhang et al., 2005). It is constituted with its consistency proof based on assumptions, essentially on the concavity of T wave. The offset fiducial is detected on the basis of the fact that maximum of the computed indicator inside each cardiac cycle coincides with T wave end.

Mathematical models of ECG have also been applied to waveform detection. Morphological model of

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one P-QRS-T complex is formulated using a set of ordinary differential equations. It is fitted to ECG signal segments by tuning the model parameters, and then used to locate the waveform boundaries (McSharry et al., 2005). These methods are in principal noise-insensitive and easily adapted to the change in ECG morphology, but they are highly computationally expensive and also suffered to parameter overheads.

While investigation of T wave delineation methods, it is found that each method has own strength(s) and weakness(es). In this paper, a novel method of T wave delineation is proposed. It is consisted of a pair of new approaches that resulted an efficient and robust way to delineate T wave in ECG. Both approaches are used lowpass filter for ECG signal correction from baseline oscillations. For an infallible detection of T wave and its end fiducials, a search window is set heuristically based on the length of a typical QT interval. Adaptive thresholding technique is utilized to detect the true presence of T wave in each heartbeat. The determination of onset (T_{onset}) and offset (T_{offset}) fiducials of T wave is resulted using the approach of (1) derivative curve analysis and (2) waveform curvature analysis. The resulted fiducials obtained from both the approaches are fused to delineate the final T wave ends.

The reminder of this paper is organized as follows. In Section 2 the schematic description of automated T wave delineation is presented. A high level description of the method used for heartbeat detection is also summarized in this section. A novel method of T wave delineation, consisting a pair of new approaches namely, derivative curve analysis and waveform curvature analysis is given in Section 3. In order to evaluate the performance of the proposed method, the results of validation and its significance are presented in Section 4. A comparison of results with other published methods are also given in this section. Finally, conclusions are drawn in Section 5.

2 SYSTEM DESCRIPTION

The automated delineation of T wave concerns ECG signal analysis and diagnostic method. The correction of the signal from non-signal artifacts including digitization and sampling is the concern of signal analysis. The schematic diagram of the automated T wave delineation system is shown in Figure 1. The task of T wave delineation carries out in following stages: The preprocessing stage consists of signal acquisition and heartbeat detection. The ECG data is acquired from the individuals and subsequently it is digitized. The digitized signal is passed to the heartbeat detection module. The heartbeat detection module utilizes QRS complex delineator algorithm which is implemented using the method of Pan and Tompkins with some improvements (Pan and Tompkins, 1985). The algorithm can be divided into filtering and decision rules. The aim of filtering of the signal is to generate a windowed (or time limited) estimate of the energy in the QRS frequency band. It is achieved by applying the following tasks: (1) lowpass filter of cutoff frequency $16Hz$ and delay of nearly $20ms$, (2) highpass filter of cutoff frequency $8Hz$ and delay of nearly $60ms$, (3) derivative unit that extracts slope information of delay nearly $5ms$, (4) absolute value function that causes QRS detector to be less gain-sensitive while Pan and Tompkins have used squaring function that caused nonlinear amplification, and (5) moving window integrator that captures QRS complexes in ECG. The average size of moving window is set to $80ms$ wide while in the original algorithm window has been set to $150ms$ wide that allowed the wider QRS complexes produced by the Premature Ventricular Contractions (PVC) and the merging of QRS complex with T wave. After filtering, the signal is free from noise and noise artifacts. The signal is then ready for the delineation of QRS complexes. The decision rules are used that make a distinction between QRS event and the noise event. The rules are framed from the physiology of the normal QRS complex in the ECG while the detection of QRS peak are carried out using adaptive thresholding technique.

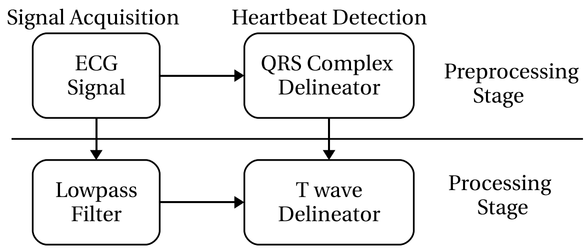

Figure 1: Schematic description of automatic T wave delineation.

In order to determine the windowed region for the existence of a normal T wave, the end fiducial of QRS complex (QRS_{offset}) is to be delineated. The fiducial QRS_{offset} is delineated according to the location and the convexity of R peak. The search region for QRS_{offset} is set according to the width of QRS complex relative to FP (R peak). Within the region, the signal is traced in time-forward order and search the sample where slope is lesser than quarter of minimum slope. In order to insure that found QRS_{offset} position is not an inflection some adjustment surrounding to the detected position need to be performed.

The computed QRS_{offset} fiducial is then passed to

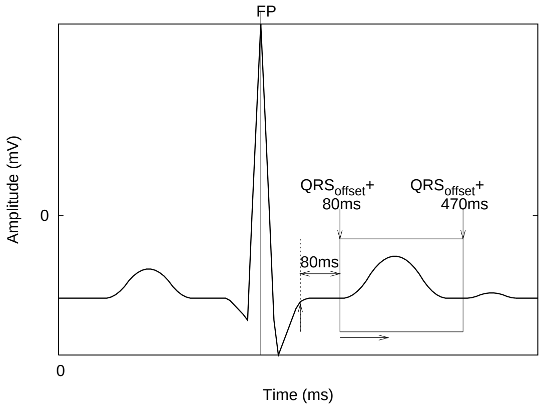

Figure 2: Setting of the search window for T wave delineation.

the processing stage at T wave delineator. The delineator uses this fiducial as a reference for the setting of search window where the proposed delineation approaches are implemented.

3 T WAVE DELINEATION

The delineation is concerned to the detection of characteristic waveform and its limits. The processing steps utilize for T wave delineation includes lowpass filtering, setting of a search window and the threshold estimation. For the reliable delineation of T wave, oscillatory patterns of the isoelectric potential must be minimized. It can be achieved by filtering of the ECG signal through a second order recursive lowpass filter (Lynn, 1977) of following time difference equation,

$$y_{nT} = 2*y_{(n-1)T} - y_{(n-2)T} + x_n - 2*x_{(n-4)T} + x_{(n-8)T} \quad (1)$$

where x_n represents the data sample of size n at discrete instant of time T. At sampling frequency of 100 *Hz*, T is found to be 10 *ms* and processing delay caused by the filter is nearly 30 *ms*.

Prior to start of the delineation process, a temporal window (search window) is defined that determines a probable region of the existence of T wave in each heartbeat. The boundaries of the search window are set heuristically relative to QRS_{offset} fiducial as shown in Figure 2. The search window that approximately contains the T_{onset} and T_{offset} fiducials is extended from $QRS_{offset} + 80ms$ to $QRS_{offset} + 470ms$ positions in each heartbeat. It can also observed that the segment of $80ms$ from QRS_{offset} fiducial is excluded from the search window because this is the time prior to repolarization of ventricles that have the negligible stimulation. Similarly, the right boundary of the search window is set according to the duration of depolarization to repolarization of the ventricles.

In order to discuss the main features of the proposed T wave delineator the morphology of the waveform is considered as positive as shown in Figure 2. The other morphologies of T wave can be treated similarly.

3.1 T Wave Detection

The procedure for detection of T wave from each beat of the ECG signal is as follows: First of all, peak of the entitled signal which is the signal within the search window is determined using the time derivative approach. Using adaptive thresholding technique, one can classify that detected peak is a true peak or a non peak of T wave. The threshold is calculated using the estimates of peak heights and the level of high frequency noise present in the beat. The threshold (ϑ) is set between the mean of peak height (μ_{peak}) and the mean of high frequency noise ($\mu_{HF_{noise}}$) according to the formula,

$$\vartheta = C_\vartheta * \left\{\mu_{peak} - \mu_{HF_{noise}}\right\} \quad (2)$$

where the threshold coefficient (C_ϑ) lies between 0 and 1. This experiment is conducted on C_ϑ = 0.23. The mean of peak height is estimated from the height of five recently detected peaks. The mean of high frequency noise is estimated from the level of high frequency noise (HF_{noise}) present in the detected peak using the following approach: The beat is firstly passed to a highpass filter of following time difference equation,

$$y_{nT} = x_{nT} - 2*x_{(n-1)T} + x_{(n-2)T} \quad (3)$$

The level of artifact signals can be estimated by taking the mean of y values of five consecutive samples. Then maximum of the means is computed for the entire beat. Let it be denoted as HF^{MA}_{noise}. Finally, a noise metric is obtained using the ratio of HF^{MA}_{noise} and R wave peak height ($h_{R_{peak}}$) according to the formula,

$$HF_{noise} = \frac{HF^{MA}_{noise} * \left(\frac{C_1}{5}\right)}{\left(\frac{h_{R_{peak}}}{C_2}\right)} \quad (4)$$

where the parameters (C_1, C_2) can be determined and set through the experiment. These values are set as $C_1 = 50$ and $C_2 = 4$ during the experiment.

3.2 End Fiducials Detection

The beginning of T wave is concerned to the start of ventricles repolarization which is raising (dropping for negative T wave) slowly while the end of T wave is concerned to the end of repolarization cycle which is terminating much faster. The changes resulted from abnormal function of epicardium and/or endocardium can also be seen in the latter part of T wave. Along to that, it is also noticed that its end segment shows a relatively lower stimulation in comparison to the level of noise present in the beat. That makes the detection of end fiducials of T wave, especially T_{offset} more cumbersome. Keeping the concern of these observations, the end fiducials of T waves, T_{onset} and T_{offset} are to be determined efficiently and more robustly using the following proposed approaches.

Both approaches utilize a linear derivative filter which corrects ECG signal from isoelectric oscillations. The first approach takes the advantage of time derivative to capture the signal variations. Furthermore, it determines T_{onset} and T_{offset} fiducials through derivative curve analysis which is obtained from the filtered signal. The approach produces better delineation results when the end positions of T wave are relatively free from local noise. For the cases, when the end positions of T wave are contaminated highly with local noise then it yields less accurate results. This is due to the sensitiveness of time derivative to the local noise. The pitfall of the first approach can be overcame in the non-derivative based second approach. The implementation bases of second approach is the assumption that the curvature of T wave near to its ends is convex. It extracts the T wave end fiducials using the analysis of the curvature toward both ends. The accuracy of the delineated results of this approach is highly depends on the assumption that the end fiducials of T wave are found at the sample corresponding to minimum radius of curvature of its waveform at both ends. These results are reported more robust to the local noise than most obvious derivative measure.

3.2.1 Derivative Curve Analysis

This approach utilizes the advantage of time derivative to capture the signal variations. The derivative approximation can be implemented using the following difference equation,

$$y_{nT} = x_{nT} - x_{(n-1)T} \tag{5}$$

where the delay of the derivative filter is set to nearly $10ms$ at sampling frequency of $100Hz$. A snapshot of the filtered signal and the signal after implementing derivative approximation is shown in Figure 3. For determining T wave end fiducials, process starts with finding the peak of derivative signal within the search window. The peak is determined at the location where maximum change in the slope is occurred. Let this

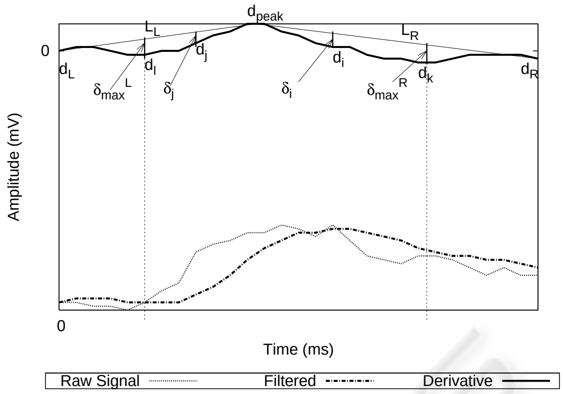

Figure 3: Detection of T wave end fiducials using derivative curve analysis within the search window.

location be denoted as d_{peak}. The procedure to determine the T_{offset} fiducial is as follows: Once d_{peak} is known, derivative signal is traced from d_{peak} to d_R positions in time-forward order. The d_R position can be set at the right most boundary of the search window i.e., $QRS_{offset} + 470ms$. Let a line L_R is drawn extending from d_{peak} position to d_R position where the coordinates of these positions are (x_{peak}, y_{peak}) and (x_R, y_R) respectively. Thus, the equation of L_R can be formulated as,

$$L_R \equiv y - y_{peak} = Slope * (x - x_{peak}) \tag{6}$$

where $Slope$ can be computed by,

$$Slope = \frac{y_R - y_{peak}}{x_R - x_{peak}} \tag{7}$$

Along with the entitled signal, vertical offset of each sample in $[d_{peak}, d_R]$ to the line L_R is computed. Let d_i be some position in $[d_{peak}, d_R]$ in the derivative signal whose coordinate be (x_i, y_i). The vertical offset (δ_i) corresponds to d_i, can be computed using the following formula,

$$\delta_i = \mid y_{peak} + \frac{(y_R - y_{peak})}{(x_R - x_{peak})} * (x_i - x_{peak}) - y_i \mid \tag{8}$$

Maximum among δ_i's is selected. The desired position at which the vertical offset of the entitled signal is maximum, is the position of T_{offset}. The found sample at position d_k where vertical offset is maximum e.g., $\delta^R_{max} = Max(\delta_i)$ is the T_{offset} fiducial as shown in Figure 3.

A similar approach is used for the detection of T_{onset} fiducial within the search window. The derivative signal is traced from d_{peak} to d_L position in time reverse order where the position d_L is set at leftmost boundary of the search window, i.e. $QRS_{offset} + 80ms$ as shown in Figure 3. In the derivative signal, a line L_L is drawn extending from d_{peak} to d_L position. Let the coordinate of d_L be (x_L, y_L). Along to the derivative signal, vertical offset δ_j is computed for each position d_j (where $d_j \in [d_{peak}, d_L]$) to the line L_L in time reverse order according to the formula,

$$\delta_j = \mid y_{peak} + \frac{(y_L - y_{peak})}{(x_L - x_{peak})} * (x_j - x_{peak}) - y_j \mid \quad (9)$$

where (x_j, y_j) is the coordinate corresponding to position d_j. Among all d_j's, a position is found where the value of the vertical offset (δ_j) of the entitled signal is maximum, i.e., $\delta^L_{max} = Max(\delta_j)$. The found position d_l returns the T_{onset} fiducial as shown in Figure 3.

3.2.2 Waveform Curvature Analysis

It is a non derivative based approach which is capable to limits the noise sensitivity of the cardiac signal and determines T wave end fiducials using the analysis of waveform curvature found at its ends.

Notations and Heuristics Basis. It is assumed that the origin of a T wave which a stage prior to ventricular repolarization and the end of T wave which is a stage prior to the end of ventricular stimulation, exhibit convex shapes at ends. It means, two convex regions can be considered at the neighborhood of T wave ends. The boundaries of both convex regions are extended towards peak of the waveform so that it becomes the common extremity of both regions. Let t_1 and t_2 are two time instances corresponding to the beginning and the end of T wave as shown in Figure 4. Consequently, the aim is to determine the time instances t_1 and t_2 as waveform end fiducials whose neighboring regions are convex. Let these regions are separated by the peak position, t_{peak}. The proposed approach determines T wave end fiducials, T_{onset} and T_{offset} through tracking down the entitled signal and finding the sample of minimum radius of curvature at both convex regions which is found to be more robust to local noise.

This approach starts its processing with the filtered signal which is corrected from signal oscillations around isoelectric line. A search window is set heuristically and an interval $[t_L, t_R]$ is delimited inside the search window in each beat of the ECG. The interval is delimited with an observation that the time positions t_1 and t_2 which correspond to T wave ends are completely inside the interval and the time positions t_L and t_R are on opposite side of t_{peak}. The peak position can be determined by finding of local maximum, while the extremities of the interval, t_L and t_R can be determined by finding of local minimum at both sides of t_{peak} in the entitled signal within the search window.

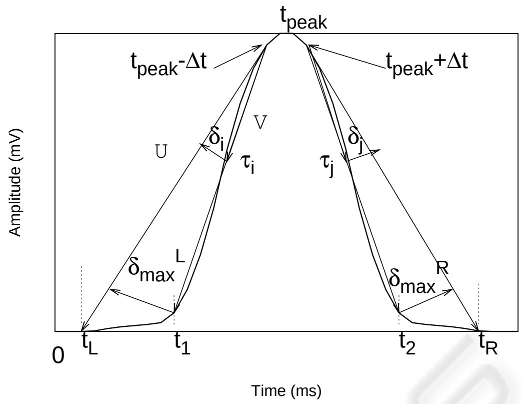

Figure 4: Detection of T wave end fiducials using waveform curvature analysis within the search window.

Assumption 1. *The segments of T wave within the intervals* $[t_{peak}, t_L]$ *and* $[t_{peak}, t_R]$ *are convex.*

Typically, T wave is convex in the neighborhoods of time instances t_1 and t_2 while it shows concaveness in interval $[t_1, t_2]$. It is acknowledged from the morphology of T waveform that the onset of T wave (i.e., t_1) and the time instant t_L which limits this onset of the waveform are laid on isoelectric line. The deflection of T wave shows the time evolution of electrical activity caused by ventricular repolarization which starts after the electrical activity caused by delayed depolarization of ventricles. It shows a significant time gap ($\sim 80ms$ in normal objects) between the start of ventricular repolarization and the late ventricular depolarization where cardiac impulse neutralizes each other and resulting approximately zero difference in electrical potential. This time gap is referred as isoelectric period. In this consideration it is also assumed that the interval $[t_L, t_1]$ is strictly inside the isoelectric period.

Similarly, the offset of T wave (i.e., t_2) and the time instant t_R which limits the onset of the waveform are laid on isoelectric line. During the interval $[t_2, t_R]$, cardiac muscles are prepared for next cycle of the heartbeat. The preparation time of myocardium prior to the start of next cycle of the heartbeat is substantially larger, while the impulse deflections during this period are insignificant. Thus, this period can be considered as isoelectric period. Similarly, it is also assumed that the interval $[t_2, t_R]$ is strictly inside the isoelectric period.

Proposition 1. *Under assumption 1 and the fixing of time differences between following intervals:*

1. $(t_{peak} - \triangle t,\ t_L)$ *and* $(t_{peak} - \triangle t,\ t_{peak} - \tau_i)$*; where* $\tau_i \in [t_{peak} - \triangle t, t_L]$*;*
2. $(t_{peak} + \triangle t,\ t_R)$ *and* $(t_{peak} + \triangle t,\ t_{peak} + \tau_j)$*; where* $\tau_j \in [t_{peak} + \triangle t, t_R]$ *and* $\triangle t \geq 0$.

the time instances t_1 and t_2 can be determined as the position of minimum radius of curvature between time differences 1 *and* 2*, respectively.*

Proof: For case 1 the waveform is traced from t_{peak} to t_L position in time reverse order. Assume that $\widetilde{U}$ and $\widetilde{V}$ are directed line segments drawn between the time difference ($t_{peak} - \triangle t,\ t_L$) and ($t_{peak} - \triangle t,\ t_{peak} - \tau_i$) respectively as shown in Figure 4. Here, point of interest is the time instance t_1 which is the position of minimum radius of curvature of the waveform segment in interval $[t_{peak}, t_L]$. The radius of curvature is computed using the principal of vector cross product between two directed line segments $\widetilde{U}$ and $\widetilde{V}$. Let δ_i be the perpendicular offset of two directed line segments $\widetilde{U}$ and $\widetilde{V}$ as shown in Figure 4 then δ_i can be determined using following formula,

$$\delta_i = \mid \widetilde{V} \mid sin\theta \tag{10}$$

where,

$$sin\theta = \sqrt{1 - \frac{\left(\widetilde{U}.\widetilde{V}\right)^2}{\mid \widetilde{U} \mid^2 \mid \widetilde{V} \mid^2}} \tag{11}$$

Let the definition of line segments in time amplitude system be given as $\widetilde{U} = \left(\widetilde{U_t}, \widetilde{U_A}\right)$ and $\widetilde{V} = \left(\widetilde{V_t}, \widetilde{V_A}\right)$, then δ_i can be computed using Eqn. (10) and (11) as follows,

$$\delta_i = \frac{\mid \widetilde{U_t}\widetilde{V_A} - \widetilde{U_A}\widetilde{V_t} \mid}{\sqrt{\widetilde{U_t}^2 + \widetilde{U_A}^2}} \tag{12}$$

In general, the perpendicular offset δ_i can be determined using Eqn. (12) at any time instance τ_i, where $\tau_i \in [t_{peak} - \triangle t, t_L]$.

Once the perpendicular offsets (for $\forall \tau_i$) are known, the position of time instance corresponding to minimum radius of curvature can be determined by finding of the sample where δ_i is maximum. Let it be ${\delta_{max}}^L$, i.e.,

$${\delta_{max}}^L = \text{Max}\left\{\delta_{t_{peak} - \triangle t}, \ldots, \delta_{t_L}\right\} \tag{13}$$

It returns the position to the time instance t_1.

Similarly, for case 2 one can determine the directed line segments $\widetilde{U}$ and $\widetilde{V}$ between the time difference ($t_{peak} + \triangle t,\ t_R$) and ($t_{peak} + \triangle t,\ t_{peak} + \tau_j$), respectively. The perpendicular-offset δ_j between the directed line segments can be determined by tracking the segment of signal from t_{peak} position to t_R position in time forward order for all τ_j, where τ_j is in $[t_{peak} + \triangle t, t_R]$ as shown in Figure 4. Finally, the time instance corresponding to minimum radius of curvature of the segment in the interval $[t_{peak}, t_R]$ can be determined by ${\delta_{max}}^R$, where ${\delta_{max}}^R = \text{Max}\left\{\delta_{t_{peak} + \triangle t}, \ldots, \delta_{t_R}\right\}$. It returns the position to the time instance t_2.

The proposed approach extracts T wave end fiducials in two stages. In the first stage, peak position is determined by finding of local maximum in the region surrounding to T wave whose boundaries are limited through the search window in each heartbeat. In the second stage, T_{onset} and T_{offset} fiducials are determined by tracking downhill the filtered signal and find the location of minimum radius of curvature at both ends. Experimental result shows that the detected fiducials are more robust to high frequency noise in the beat.

3.3 Fusion of Delineation Performance

In this work, T wave delineator takes the advantage of both the proposed approaches. It is found that the approach based on the analysis of waveform curvature returns more accurate T wave end fiducials when the assumption 1 is satisfied. That is the region surrounded to onset and offset positions of T wave is convex. Otherwise, the approach based on the analysis of derivative curve produces better result. Thus, for a reliable and accurate detection of T wave end fiducials, the delineation results obtained from both the approaches are fused. In this work, the fusion of delineated results is obtained by taking mean of both the results.

3.4 Other T Wave Morphologies

T wave morphologies can be generally classified as positive, negative, and biphasic as shown in Figure 5. The delineation approaches proposed here are formulated for the positive T waves of the ECG. The other T wave morphologies can be treated as follows: For negative T wave the proposed approaches perform equally well. The only difference finds in this case is the detection of time instance to the peak of the entitled signal which is associated to the local minimum instead of local maximum in both approaches. In biphasic case, local maximum-minimum can be determined for biphasic positive-negative T wave and minimum-maximum can be determined for biphasic negative-positive T wave. The end fiducials of biphasic (positive-negative) T wave can be determined by tracking of the entitled signal downhill from maximum position in time-reverse order for the detection of T_{onset} and uphill from the minimum position in time-forward order for the detection of T_{offset} in both approaches. The end fiducials of biphasic (negative-positive) T wave can be determined vice-versa.

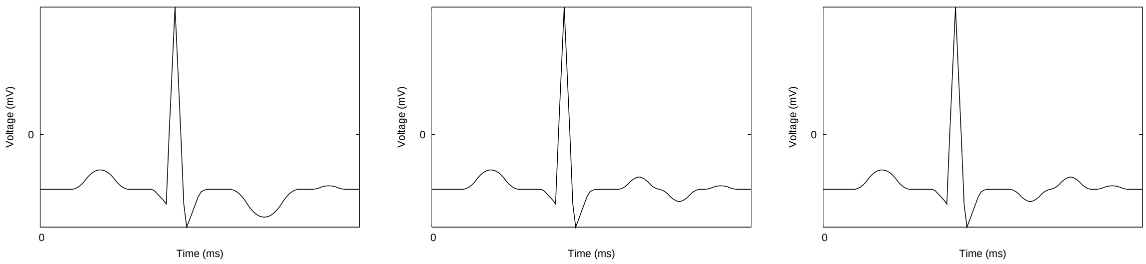

Figure 5: Examples of different morphologies of T wave, (a) Negative, (b) Biphasic positive-negative and (c) Biphasic negative-positive.

Table 1: Detection performance of T wave in QT database. *Se* measures the waveform detection sensitivity ($Se(\%) = 100 \times TP/(TP+FN)$). The estimate of the detection of true waveform is determined by P^+ ($P^+(\%) = 100 \times TP/(TP+FP)$). *Acc* determines the measurement of delineation accuracy ($Acc(\%) = 100 \times (TP+TN)/(TP+TN+FP+FN)$.

Technique	Parameters	T wave
	# annotations	3542
WT Detector (Martinez et al., 2004)	TP	N/R
	FP	N/R
	FN	N/R
	Se (%)	99.77
	P^+(%)	97.79
	Acc(%)	N/R
	# annotations	2500
MD Detector (Sun et al., 2005)	TP	N/R
	FP	N/R
	FN	N/R
	Se (%)	99.6
	P^+ (%)	N/R
	Acc (%)	N/R
	# annotations	20000
Proposed Work	TP	19980 (999@1000)
	FP	180 (9@1000)
	FN	20 (1@1000)
	Se (%)	99.9
	P^+ (%)	99.1
	Acc (%)	99.01

The approaches utilize for T wave delineation typically determine the morphology of its waveform a priori to its onset and offset detection. A simple approach that distinguishes biphasic T wave with its other waveforms (e.g., positive T wave or negative T wave) can be the searching of zero crossing in the signal within the search window. If there is an existence of zero-crossing then T wave is biphasic; otherwise it is either a positive T wave or a negative T wave.

4 EXPERIMENTAL RESULTS

The performance of the proposed T wave delineator is evaluated on Physionet QT database (Laguna et al., 1997) which served as a reference for the validation and the comparisons of T wave delineation methods. The performance of T wave detection and the determination of its end fiducials are validated on manually annotated samples of this database.

QT database is a mixed database contains 105 fifteen minutes excerpts of two-channel ambulatory ECG recordings. The recordings are digitized at 250 *Hz* per channel with 11-bit resolution over a 10 mV range. It contains following databases, 15 from MIT-BIH Arrhythmia database, 6 from MIT-BIH ST Change database, 13 from MIT-BIH Supraventricular Arrhythmia database, 10 from MIT-BIH Normal Sinus Rhythm database, 33 from European ST-T database, 24 from Sudden Death from MIT-BIH database and 4 records from MIT-BIH Long Term ECG database. In this work the MIT-BIH Arrhythmia database and MIT-BIH Normal Sinus Rhythm database, first channel recordings have been used for analysis.

In this experiment, the performance of T wave detection is measured on following terminologies: *TP* is the true detection of T waves. FN returns the waves those are not registered in the automatic delineation process. FP returns those waves that are detected incorrectly. In order to quantify the accuracy of the proposed delineator mean error (μ_ε) and standard deviation (σ_ε) of the differences between the annotation results and the automated delineator results are also computed. The mean error is used to measure the closeness between them while σ_ε measures stability in the delineation results. Sensitivity (*Se*), positive predictivity (P^+) and accuracy (*Acc*) are also computed to measure the detection performance.

Table 2: End Fiducials detection performance of T wave and its comparison with different methods in QT database. (N/R: Not Reported)

Technique	Parameters	T_{onset}	T_{offset}
	# annotations	3542	3542
WT Detector (Martinez et al., 2004)	$\mu_\varepsilon \pm \sigma_\varepsilon$ (*ms*)	N/R	-1.6 ±18.1
	Se (%)	99.77	99.77
	P^+ (%)	97.79	97.79
	Acc (%)	N/R	N/R
	# annotations	2500	2500
MD Detector (Sun et al., 2005)	$\mu_\varepsilon \pm \sigma_\varepsilon$ (*ms*)	7.9±15.8	8.3 ±12.4
	Se (%)	99.8	99.6
	P^+ (%)	N/R	N/R
	Acc (%)	N/R	N/R
	# annotations	20000	20000
Proposed Work	$\mu_\varepsilon \pm \sigma_\varepsilon$ (*ms*)	0.9±7.8	5.3±9.7
	Se (%)	99.9	99.8
	P^+ (%)	99.1	99
	Acc (%)	99.01	98.8
Tolerance Limit (The CSE Working Party, 1985)	σ_ε (*ms*)	...	**30.6**

4.1 Waveform Detection

The performance of the proposed delineator for T wave detection on Physionet QT database is shown in Table 1. In this study, first 8 seconds of the selected record is used for training purpose and setting of the parameters. Therefore this portion of the sample is exempted from validation. From rest of the sample, 1000 peak annotations are selected. The experiment is conducted on 20 records and the results are shown in Table 1 which are compared with the results obtained from some of the well known methods, WT detector (Martinez et al., 2004) and MD detector (Sun et al., 2005). Among the 1000 peak annotations of T waves, the proposed delineator is detected 999 waves correctly and 9 waves incorrectly while it is left only one wave from the detection, on an average from one record. It is achieved the detection Se of 99.9% and P^+ of 99.1% which is higher than any of the published results. The accuracy of T wave detection is measured and found more than 99 % which is not reported (N/R) in the other methods.

4.2 End Fiducials Detection

The statistical results for μ_ε, σ_ε, *Se*, P^+ and *Acc* of T_{onset} and T_{offset} fiducials obtained from the proposed delineator are shown in Table 2 and are compared with other published results. The accepted σ_ε tolerance from the measurements recommended by CSE (The CSE Working Party, 1985) is also given in the last row of the this Table.

The delineator takes the advantages of the proposed approaches and achieves outstanding delineation performance on the evaluated database. Lower values of mean error and standard deviation for T_{onset} fiducial are observed in comparison to MD detector while these values are not reported in WT detector. The mean error for T_{offset} fiducial obtained in this work (5.3 *ms*) is found better than MD detector (8.3 *ms*) while WT detector performed best (-1.6 *ms*). The standard deviation for T_{offset} fiducial is reported better than any of the published results and found well within the acceptable limit recommended by the CSE working party. This signifies the robustness in the detection of the end fiducial of T waveform. Nevertheless, the end fiducial is delineated much efficiently with the $Se = 99.8\%$, $P^+ = 99\%$ and an accuracy of 98.8%. The mean error and standard deviation for T_{onset} fiducial are also found better than both WT and MD detectors. These results of T wave delineation are better than any of the published methods.

5 CONCLUSIONS

This paper has presented a novel method of T wave delineation which showed an efficient detection of T wave and its end fiducials in the single-lead electrocardiogram. The performance of the proposed system has validated on standard annotated database on a total of 20000 (20x1000) peak annotations. The results have shown a reliable and accurate delineation of

T wave which outperformed in comparison to other published results on the referenced database. The method has detected T waves and their end boundaries with an accuracy of more than 99% annotated by cardiologists in the ECG.

The delineation errors in this experiment have found well within the referenced inter-cardiologist observations, especially for the detection of T wave end. The remarkable performance of T wave delineation has been achieved, due to the utilization of different approaches of basis the time derivative and other than the time derivative. The mean error and standard deviation of T wave end fiducials have been found smaller than one inter sample time which is 10 *ms*.

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