Automatic Wave Onset and Offset Determination in ECG Signals: Validation with the CSE Database

P Laguna*, D Vigo, R Jane, P Caminal

Institut de Cibernetica (UPC-CSIC), Barcelona, Spain
*Centro Politecnico Superior, Universidad de Zaragoza, Spain

Abstract

This paper presents a method to automatically determine the characteristic points (onset and offset) of the P, QRS and T waves in the multi-lead ECG signals from the 15 standard leads. From these points significant clinical parameters are measured, in particular PR interval, PR segment, QRS interval, ST segment and QT interval. The method makes use of the differentiated low-pass filtered ECG signal and information about wave shape. The procedure begins applying a multi-lead QRS detector to recognize beat activity in each lead. After that, waves onset and offset are searched in each lead, and a selection is done to consider those limits from leads where the electrical activity of the heart has longer temporal projection. The method performance has been evaluated with the CSE multi-lead measurement database, comparing our method results with those from other programs and manual measurement. Our method improves the T wave end measures, since it results in much more agreement with the clinical experts that with other programs. Same evaluation has been done with the interval values (error mean and standard deviation), and the results are lower than the tolerances recommended by the CSE experts.

1 Introduction

The Electrocardiographic signal (ECG) is characterized by a recurrent wave sequence (P, Q, R, S, T) related with each beat. Time intervals defined from onset and offset of different waves are significant in electrocardiographic diagnosis. The most important intervals are the RR interval, PR interval, PR segment, QRS interval, ST segment and QT interval. Thus, P, QRS and T waves onset and offset must be determined. Some algorithms have been specifically proposed to estimate QRS onset and offset [1], others have been proposed to estimate QT interval limits [2] or to estimate onset of P and QRS waves and offset of P, QRS and T waves [3,4]. When signal is free of noise, the algorithm have an acceptable performance but it decreases when noise contamination appears. Specially, the T offset point measures present a significant disagreement between the program and the referee measurements because programs give earlier T offset than manual experts [4]. In this paper we present a general method to estimate the onset and offset of P, QRS and T waves in a multi-lead ECG record, that gets a good agreement between program and manual referee results, even for the T offset point.

This method is based on the multi-lead generalization of a previously related procedure for single-lead measurement of the QT interval [2], and posteriorly used for single-lead onset and offset determination [5]. It makes use of the differentiated ECG signal and information about wave shape. The differentiation process avoids problems with baseline drift given that low frequencies are then attenuated. The system implements criteria to establish wave presence or absence in each lead according to the relative differentiated signal magnitude in the different waves. With the information about wave presence and the differentiated signal, the system estimates regular or inverted P wave, QRS complex pattern as composed of different Q, R, S, R' sequences, and T wave shape (regular, inverted, or bi-phasic) [6]. With the information about waves onset and offset in each lead, a procedure is applied to select the wave limits from those leads where the electrical activity has longer temporal projection.

The method has been applied on ECG records of the MIT-BIH database, and validated with the CSE multi-lead measurement database.

2 Methods

The procedure to determine significant points is composed of several steps: preprocessing, multi-lead QRS detection, fibrillation process rejection, waves location and wave onset and offset determination.

2.1 Preprocessing:

The first step consists of a filtering process for noise reduction and a non linear transformation to improve QRS detection [7]. The linear filtering uses a second order band-pass Lynn filter (0.8-18 Hz) to attenuate baseline drift and high frequency contamination. Once the band-pass filtered signal (ECGPB) is reached a low-pass differentiator is applied to get the information about changes in the signal slope. This differentiated signal is called ECGDER. The non linear transformation we use is the one described in [7].

2.2 Multi-lead QRS detection:

The multi-lead QRS detector used in this work is an adaptation of the single-lead one proposed by Pan and Tompkins [7] considering information of the signal slope. From the ith QRS complex positions of each j lead ($QRS_j(i)$), we only consider as QRS complexes in each lead, those whose positions do not

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differ more than 90 ms from one lead to the other.

2.3 Fibrillation process rejection:

When a fibrillation process appears there is no sense in measuring P, QRS and T onsets and offsets. The fibrillation process is detected by using the procedure presented in [8].

2.4 Waves location:

The QRS positions ($QRS_j(i)$) given by the detector may be Q, R or S wave peaks. From the $QRS_j(i)$ position in the ECGDER (zero-crossing in this signal) we search for the nearest peak positions before (p_b) and after (p_a). According to the polarity and relative value of these peaks we decide if $QRS_j(i)$ in the ECG belong to Q, R or S wave position. The adjacent wave positions are detected as the nearest zero-crossing points to $QRS_j(i)$ in ECGDER. To admit these adjacent detected points as wave positions, the time distance between waves must be in the range of physiologically significant intervals, and the maximum slope associated with these waves must be bigger than a threshold of the maximum slope associated with the QRS complex. The threshold value is experimentally adjusted and is different for Q, R, S or R' waves, ranging from 3 to 10% of the maximum QRS slope value. With this procedure we have located the eventual Q, R, S and R' wave positions.

Next, we search for P and T wave positions. These waves have lower frequency components than the QRS complex. Then, we again apply a low-pass filter (cutoff frequency 12 Hz) to ECGDER to remove remainding noise. In this filtered signal (DERFI) we define a window of 155 ms starting 225 ms before the R position. This window is shortened when previous T or next Q waves are in it. In this window we search for the maximum and minimum value. If these values are bigger than 2% the maximum slope value of the QRS complex we consider presence of P wave, otherwise we consider P wave absence. P wave position is considered in the zero-crossing between the maximum and the minimum values in the window.

To detect T wave we define a search window in DERFI that is a function of the heart rate [2]. In this window we again search for the maximum and minimum values. According to their relative position and value we consider different shapes of T wave: regular, inverted, bi-phasic (+-) or bi-phasic (-+) [6]. T wave position is considered in the zero-crossing adjacent to the maximum or minimum value.

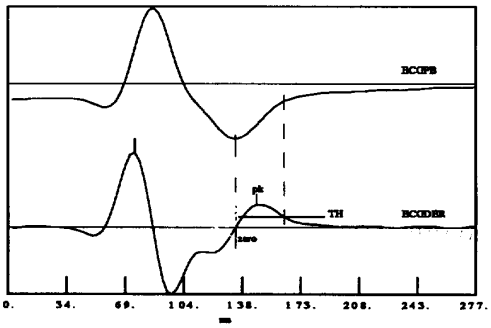

Figure 1: *Determination of QRS offset by the threshold method.*

2.5 Single-lead waves onset and offset determination:

Once we have the wave locations (zero-crossing point (*zero*) in the differentiated signal ECGDER or DERFI), we proceed to determine the onset and offset of each wave. The method used was presented in [2] for QT interval determination, and in this work we have generalized it to determine any wave limit in multi-lead ECG records. Figure 1 shows this procedure for QRS offset determination. From the *zero* point we search for the adjacent peak (*pk*) on the right (for offset) or on the left (for onset). This point is the highest slope point in the wave. With the value of ECGDER at time instant *pk* (ECGDER(*pk*)) we define a threshold (TH) as TH=ECGDER(*pk*)/*k*. Then, we determine the offset (onset) point of the wave as the forward (backward) threshold crossing point from *zero* in the ECGDER signal. The value of *k* is a constant that is experimentally adjusted and reaches its best performance for *k*=2 (P, Q and T onset and P offset), *k*=3 (S and T offset) and *k*=5 (R onset and offset). Figure 2 shows this procedure results on a single-lead ECG record from the MIT-BIH database.

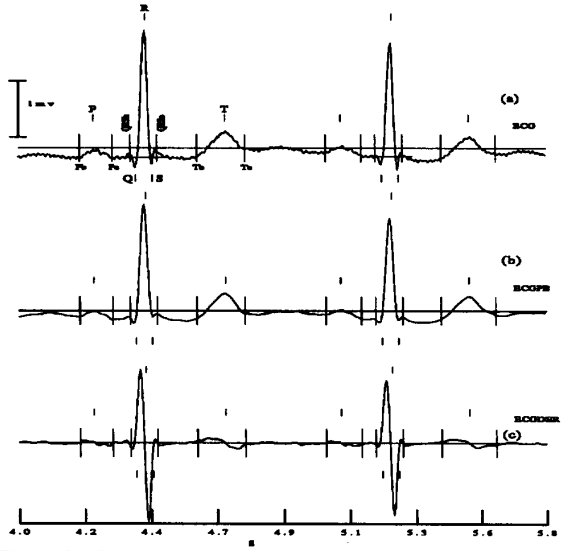

Figure 2: *Detection of characteristic points in two beats belonging to the 103 record (lead MLII) of the MIT-BIH ECG database. Short lines denote the wave positions (P, Q, R, S and T) and long lines the wave limits: P onset (Pb), P offset (Pe) and so on. a) is the original ECG, b) the ECGPB signal and c) the ECGDER signal.*

2.6 Multi-lead waves onset and offset determination:

From the previous procedure we obtain, for each characteristic point I, a set of positions I_j belonging to each *j* lead. The next step is the selection, from these I_j positions, the one that will be considered the real onset or offset of the wave. Electrophysiologically, if all I_j were correctly detected, we should select the earliest I_j for waves onset and the latest for waves offset.

However, due to noise or errors, wrong detections could have occurred in the determination of some $\mathbf{I}_j$, that may lead to an erroneous final I position. To prevent that, we apply the following procedure: We search the minimum time position (for onsets) or maximum time position (for offsets) $\mathbf{I}_j$ positions. If no more than two other leads have their $\mathbf{I}_j$ mark in the interval (*min*, *min* + δ) or (*max* - δ, *max*), the *min* or *max* $\mathbf{I}_j$ point is rejected as a possible noisy detection. The value of δ is selected according to the usual variability in manual estimations [6] and the empirical practice. Values for δ are 6, 6, 6, 10 and 12 ms for P on, P off, QRS on, QRS off and T off, respectively. After that we consider the wave onsets, offsets as the minimum, maximum of the remainding $\mathbf{I}_j$ positions.

3 Results

The single-lead procedure has been applied to different records of the MIT-BIH database. In figure 3 are displayed the results on four different records: record 106 presents a RSR' pattern, record 108 present a QS pattern, record 114 presents a W pattern and record 111 present a R wave with two peaks. In all cases the wave limits are well determined, including wave shape determination. The base line (horizontal line in figure 3) is estimated as the average ECG signal value in the PR segment of each beat, excluding first and last 15 ms in this interval.

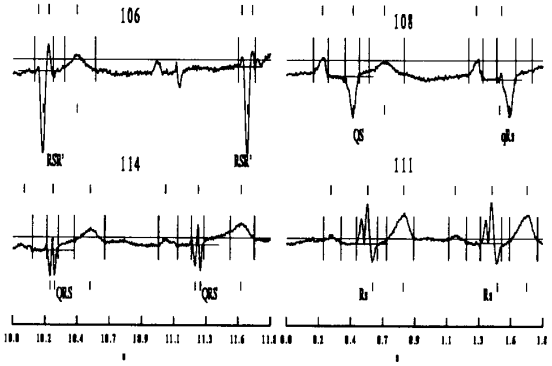

Figure 3: *Results on different ECG patterns.*

The multi-lead procedure has been applied to records of the CSE multi-lead measurements database. Figure 4 shows the results obtained on the MO1_063 record of this database. We may appreciate the improvement of multi-lead detection at the T offset point, that differs largely from leads V_2 and V_3 to the others leads like I or III.

4 Validation with the CSE database

The method to determine onset and offset has been validated with the CSE multi-lead measurement database [9]. The validation has been carried out in terms of the mean (μ) and standard deviation (σ) of the differences between: the mean referee estimates of CSE database (RE_{CSE}) or the mean program estimates of CSE database (PE_{CSE}), and our method estimates (ME) in each measured beat set. In table 1 we have these results together with the accepted tolerance for referee deviations (σ_{ref}) reported in [6]. The value $n°$ refers to the number of available measured beats reported at the CSE database for comparisons (one beat from each CSE multilead ECG records).

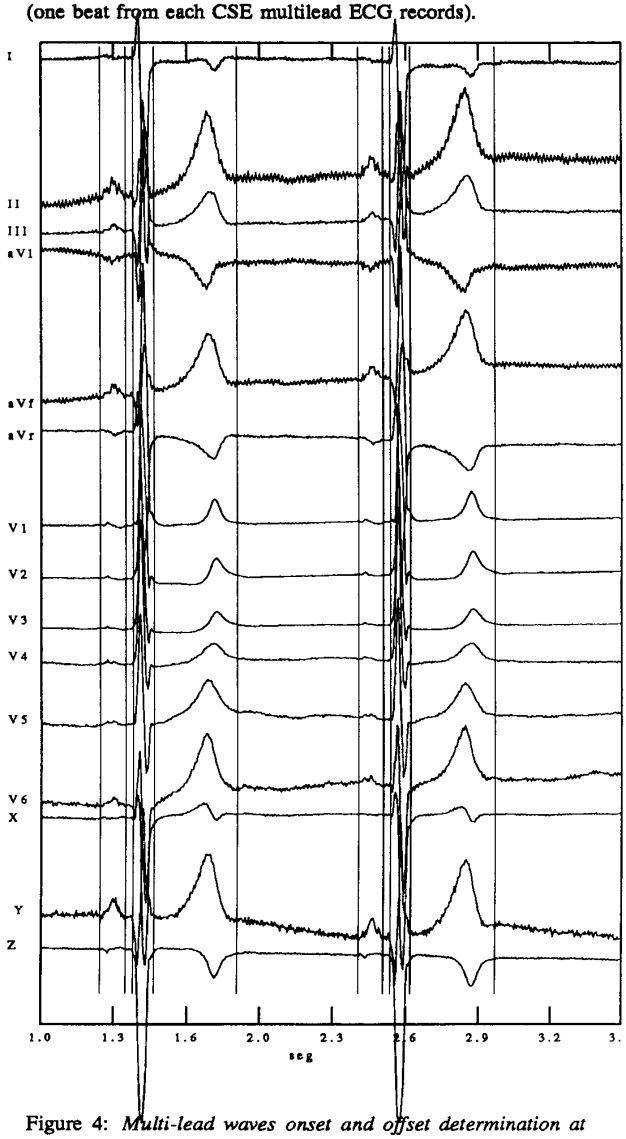

Figure 4: *Multi-lead waves onset and offset determination at the MO1_063 record of the CSE database.*

From this table 1 we see that the proposed method is an unbiased estimate (μ < sampling period = 2 ms) with deviation comparable to that of manual experts and then, for the validation sample, a valid estimate. In case of T offset point, the ME shows much more agreement with the RE_{CSE} (1.8 ms mean difference) than for the PE_{CSE} (9.7 ms mean difference). These results lead us to consider this method more accurate for T offset than the mean program estimates.

We have also validated the method in terms of the signifi-

Table 1. Waves onset and offset validation results.

ME - PE_{CSE}					
	P_{on}	P_{off}	QRS_{on}	QRS_{off}	T_{off}
n°	111	111	121	121	121
μ (ms)	-0.072	0.505	-3.587	0.083	9.700
σ (ms)	5.695	8.310	4.193	7.705	16.467
ME - RE_{CSE}					
	P_{on}	P_{off}	QRS_{on}	QRS_{off}	T_{off}
n°	30	29	30	25	26
μ (ms)	1.000	-1.034	-2.067	-0.160	1.846
σ (ms)	7.926	5.144	7.437	7.893	10.552
Accepted tolerances for referee deviations [6]					
σ_{ref}	10.2	12.7	6.5	11.6	30.6

cant interval values: P duration (P-DUR), PR interval (PR-INT), QRS duration (QRS-DUR) and QT interval (QT-INT). The validation has been done in terms of the mean and standard deviation of the differences between: the intervals measured from the mean referee estimates of CSE database (RE_{CSE}) or the intervals measured from the mean program estimates of CSE database (PE_{CSE}), and the intervals measured from the method estimates (ME). In table 2 we have these results together with the interval tolerances (μ_{tol} and σ_{tol}) reported in [10]. The value $n°$ refers to the number of available measured beats reported at the CSE database for comparisons.

Table 2. Interval validation results.

ME - PE_{CSE}				
	P-DUR	QRS-DUR	PR-INT	QT-INT
n°	111	121	111	121
μ(ms)	0.577	3.802	-3.423	13.133
σ(ms)	10.690	9.050	6.803	16.831
ME - RE_{CSE}				
	P-DUR	QRS-DUR	PR-INT	QT-INT
n°	25	23	25	23
μ(ms)	-0.400	3.217	-2.400	4.261
σ(ms)	7.095	9.812	8.679	10.274
Error limit tolerances for programs [10]				
μ_{tol}(ms)	10.0	3.5	4.5	7.0
σ_{tol}(ms)	12.0	8.0	8.0	13.5

From this table we see that the interval measures obtained with the proposed method have mean difference and standard deviation inside the expert tolerance limits.

5 Conclusions

The proposed method to determine wave limits in the ECG has been shown to be robust when noise or baseline drift are present. It allows the determination of all intervals clinically interesting in ECG records with the accuracy of a human expert. Validation of this method shows higher agreement with the experts in the T offset determination than other programs referenced at the CSE database. The information about the waves shape obtained with this method is very useful for ECG classification and cardiac diagnosis. The interval values, wave amplitudes, patterns of P, QRS and T waves, and wave presence or absence, could be used as inputs to a system that allows automatic cardiac diagnosis from ECG analysis.

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Address for correspondence:
Pablo Laguna. Centro Politécnico Superior
Maria de Luna, 3. 50015, Zaragoza, Spain.