An Algorithm for Robust Detection of QRS Onset and Offset in ECG Signals

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Abstract

This paper proposes a robust algorithm for QRS onset and offset detection in ECG signals. It mainly consists of the computation of an indicator related to the area covered by the QRS complex envelope. This algorithm was initially developed for the detection of T wave end, whose robustness and efficiency for that purpose have been previously reported. Its performances for QRS onset and offset detection have been evaluated using the PhysioNet QT database. For QRS offset detection, this new algorithm improves the best results reported in the publications about other algorithms evaluated on the same database, and for QRS onset detection, its performance is close to the best published results.

1. Introduction

As a convenient measurement of cardiac electrical activity, the electrocardiogram (ECG) provides important information for cardiac disease diagnosis. Each cardiac cycle in the ECG is characterized by successive waveforms known as P wave, QRS complex and T wave. Time intervals between onset and offset of different waves are significant because they reflect physiological processes of the heart and of the autonomous nervous system.

The QRS complex in an ECG corresponds to the depolarization phenomenon of the ventricles preceding the mechanical contraction, and it conveys useful information about the contraction. The QRS onset and offset detection is useful for the computation of QRS duration, as well as for the computation of QT and ST intervals.

Though algorithms for automatic detection of waveforms in ECG signals have been intensively studied, the robustness of these algorithms is still an important issue in clinical applications. Because of the great morphological variations in ECG signals, it is difficult to design automatic and widely applicable algorithms. This difficulty partly explains the continuous efforts made by researchers on ECG signal processing, as demonstrated by the recent publications [1–3] and by many others.

In this paper, a new algorithm is proposed to further improve the QRS onset and offset detection. The proposed algorithm mainly consists of two steps. In the first step, the envelope of the QRS complex is computed from the ECG signal based on the Hilbert transform. This envelope signal has the particularity of being a bell-shaped concave wave, and the beginning and the end of this concave wave correspond respectively to the QRS onset and offset. In the second step, an indicator related to the area covered by the envelope signal is computed. This indicator was initially designed for the detection of T wave end, whose robustness and efficiency for that purpose have been reported in [4, 5]. Its application to the QRS envelope signal has encountered a new difficulty: the width of the QRS envelope, which affects the tuning of the algorithm, can vary considerably. To overcome this difficulty, a two-stage method will be proposed in this paper.

The main computation of the algorithm is the indicator related to the area delimited by the processed signal in a moving window. This computation essentially integrating the signal makes the algorithm robust to signal acquisition noises. Another robustness aspect of the algorithm is due to its small number of tuning parameters.

The performances of the proposed algorithm have been evaluated using the QT database available in the PhysioNet website [6].

2. Method

The algorithm is composed of five steps: Bandpass filtering, R peak detection, computation of the envelope of the filtered ECG, windowing, and finally the computation of the surface indicator. These steps are detailed below.

2.1. Bandpass filtering

A bandpass filter is first applied to ECG signals for noise attenuation while preserving the essential spectral content of the QRS complex [7].

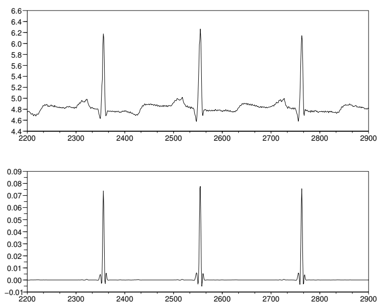

Figure 1. ECG signal and its indicator signal (bottom) for R peak detection

The cutoff frequencies of the bandpass filter are different for the detections of QRS onset and QRS offset: $[0.5\ \ 40]$ Hz for QRS onset and $[5\ \ 30]$ Hz for QRS offset. These cutoff frequencies were experimentally selected.

The filter is simply based on the Fast Fourier Transform (FFT) of the processed ECG signal. The undesired frequencies are truncated from the FFT before the application of the inverse FFT in order to obtain the bandpass filtered signal.

2.2. R peak detection

As in every method for ECG segmentation, R peak detection is a very important step because it serves as a reference for other detections. For the results presented in this paper, the R peak is detected with an indicator which takes into account the amplitude and the curvature of the ECG signal in order to distinguish the R waves from the other waves of the ECG signal [3]. An example of this indicator is shown in Figure 1.

2.3. Computation of the ECG envelope

After the R peak detection, the QRS complex envelope is computed from the bandpass filtered ECG signal. The envelope is defined as the modulus of the complex signal formed by the filtered ECG signal (the real part) and the Hilbert transform of the filtered ECG signal (the imaginary part) [8]. The Hilbert transform is very useful for signal demodulation without knowing the carrier frequency. If we consider a QRS complex as a modulated waveform, the beginning and end of the QRS complex envelope calculated using the Hilbert transform coincide with the QRS onset and offset respectively [7].

The Hilbert transform of a real signal $x(t)$ is defined by:

$$x_H(t) = \frac{1}{\pi} \int_{-\infty}^{\infty} \frac{x(\tau)}{t-\tau} d\tau \qquad (1)$$

and may be computed in the frequency domain as:

$$X_H(j\omega) = X(j\omega) \cdot [-j \cdot sgn(\omega)] \qquad (2)$$

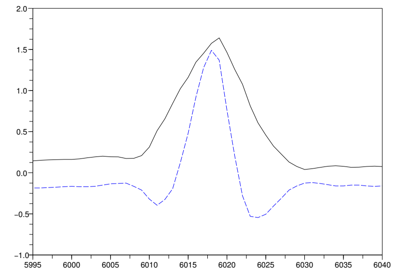

Figure 2. QRS complex (dashed line) and its envelope (solid line)

Using discrete-time notation, a complex sequence $ECG(k) + jECG_H(k)$ is formed from the real signal sequence $ECG(k)$, where $ECG_H(k)$ is the Hilbert transform of $ECG(k)$. Then, the envelope signal is defined as:

$$ECG_e(k) = \sqrt{ECG^2(k) + ECG_H^2(k)} \qquad (3)$$

Figure 2 shows a QRS complex (dashed line) and its envelope (solid line). It can be observed that the QRS complex corresponds to a hump of the envelope signal. This fact will be useful for the detection of the QRS onset and offset in the following steps.

2.4. Windowing

In order to limit the search of the QRS onset and offset, two intervals of time (search windows) in each cardiac cycle, containing the QRS onset and the QRS offset respectively, are defined: $[Rp - 300(ms), Rp]$ for QRS onset and $[Rp, Rp + 150(ms)]$ for QRS offset, where R_p is the detected R peak at each cardiac cycle. The values 300 ms and 150 ms are experimentally selected after optimization of the results.

2.5. Computation of the surface indicator

The originality of this algorithm resides in this last step: the computation of an indicator related to the area covered by the QRS envelope signal inside a moving window. This area indicator was initially designed for the detection of the T wave end, whose robustness and efficiency for that purpose have been presented in [4, 5]. Its application to the QRS envelope signal has encountered a new difficulty: the width of the QRS envelope, which affects the tuning of the algorithm, can vary considerably. To overcome this difficulty, a two-stage method will be proposed later in this section.

For each cardiac cycle, two intervals have been roughly delimited (see Section 2.4 concerning the windowing) such that the QRS onset and offset are inside these intervals with no overlap with the other waveforms (P and T). The fol-

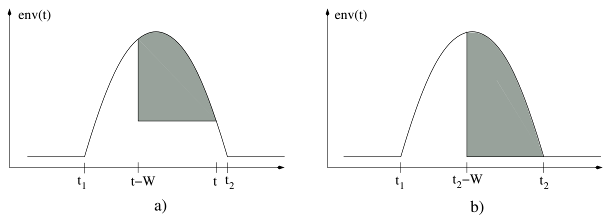

Figure 3. Illustration of the surface indicator $A(t)$ by the grey areas

lowing presentation assumes that all the computations are performed inside one of these two intervals.

For an easy understanding of the area indicator, the algorithm will be explained in continuous time (though in practice discrete time signals are processed) and only for QRS offset detection (its adaptation to QRS onset is straightforward and will not be detailed). The envelope signal in continuous time will be denoted by $env(t)$.

Throughout this section, the time instants corresponding to the beginning and the end of a QRS envelope are, respectively, denoted by t_1 and t_2 (see Figure 3 for an idealized illustration). The QRS envelope length, denoted by $L = t_1 - t_2$, is generally an unknown value.

The proposed algorithm mainly consists of the computation of an indicator $A(t)$ which reaches its maximum value when $t = t_2$. It is computed mainly through an integration operation in a sliding window. The choice of the sliding window width W will be discussed later. At each time instant t, define the indicator

$$A(t) = \int_{t-W}^{t} [env(\tau) - env(t)]d\tau \qquad (4)$$

which can be understood as the area in the interval $[t-W, t]$ under the signal $env(t)$ but above the horizontal line crossing the point $(t, env(t))$ as illustrated in Figure 3. It has been shown that, under some simple assumptions, essentially the concavity of $env(t)$, $A(t)$ reaches its maximum value at $t = t_2$. See [5] for the details.

As mentioned previously, in the case of the QRS complex, it is difficult to chose the value of W because of large variations of the QRS complex width L. In the reminding part of this section a two-stage method will be presented to deal with this problem.

Due to large variations of QRS complex width L, the value of W will be tuned for each QRS complex being processed (in contrast, W was a constant value for T wave end detection as reported in [5]). Again consider an ideal bell-shaped envelope signal as illustrated in Figure 4, with t_1, t_2 and t_p being respectively the instants of the beginning, the end and the top of the bell. For a correct detection of the QRS offset t_2, the area indicator (4) should be applied with a window width W satisfying $t_2 - t_p < W < L$. If the

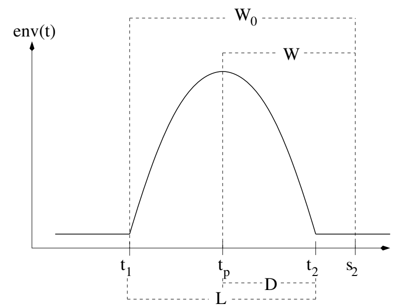

Figure 4. Two-stage choice of the window width W

value of W is too large, say W_0, then the application of the area indicator (4) detects the end of the envelope at an instant later than t_2, as marked by s_2 in Figure (4). It is then clear that $s_2 - t_p > t_2 - t_p$. If W_0 is reasonably large, s_2 should be sufficiently close to t_2 so that $s_2 - t_p < L$. Under these assumptions, $W = s_2 - t_p$ will be a good choice for another application of the area indicator (4), since it satisfies the requirement $t_2 - t_p < W < L$. These ideas are summarized into the following two-stage procedure:

1. Apply the area indicator (4) to the processed QRS envelope signal with $W = W_0$ corresponding to the largest QRS complex width that can be encountered in practice. Find the instant $t = s_2$ maximizing the indicator $A(t)$. Find also the instant $t = t_p$ maximizing the envelope signal $env(t)$.
2. Apply again the area indicator (4) to the same QRS envelope signal, but with $W = s_2 - t_p$. The QRS offset t_2 is then detected at the instant t maximizing the indicator $A(t)$.

3. Results

In this section, the performances of the proposed algorithm are experimentally evaluated. The QT database presented in [6] available on the PhysioNet website has been used for validation purposes. This database has been built by researchers specifically for the evaluation and comparison of algorithms for ECG signal segmentation. The signals in this database have been manually annotated by cardiologist experts for various events.

The database consists of 105 fifteen minutes excerpts of two channels ECG Holter recordings sampled at 250 Hz. The recordings have been chosen to include a broad variety of ECG morphologies and have been extracted from other existing ECG signal database. For each record, between 30 and 100 representative beats were manually annotated by cardiologists. The markers include mainly P wave, QRS complex, and T wave peaks, onsets and offsets. Only the QRS onset and offset annotations are used in this paper.

In order to evaluate the accuracy of the proposed algorithm, the mean and standard deviation (STD) of the

Table 1. Evaluation of the algorithms on the QT database (mean and STD indicate the mean and standard deviation of detection errors for each algorithm)

Method	QRS_{onset} $mean \pm STD$	QRS_{offset} $mean \pm STD$
nb. of annot.	3963	3963
This paper	-2.6 ± 7.1	0.7 ± 8.0
ENV	0.6 ± 7.2	1.2 ± 8.3
WT	4.6 ± 7.7	0.8 ± 8.7
LPD	-3.6 ± 8.6	-1.1 ± 8.3
EA	0.3 ± 6.6	-1.9 ± 8.3
Tolerances(STD)	6.5	11.6

differences between automatic detection and cardiologists annotations are computed in order to quantify the performance of the QRS detection algorithm (QRS onset and offset detection). These values are computed according to the method adopted in [9]. The results of our algorithm are compared with the result of 4 different detection algorithms which have been evaluated with the PhysioNet QT database in publications: LPD [10], WT [9], EA [2], and ENV [3] as shown in Table 1. This table shows the results of these algorithms and those of the algorithm presented in this paper in terms of the mean and the STD of the detection errors of each algorithm.

The numerical values for the WT and LPD algorithms come from the publication [9]. For the algorithms EA and ENV, the numerical values come from [2] and [3] respectively.

In [11], the tolerances for the STD of detection errors for QRS onset and offset are presented. These tolerances are also shown in the last row of Table 1.

4. Discussion and conclusions

A new algorithm for QRS onset and offset detection has been presented. It mainly consists of the computation of an indicator related to the area covered by the QRS complex envelope. This envelope signal has the particularity of being a bell-shaped convex wave regardless of the presence or absence of the Q and S waves.

When evaluated on the PhysioNet QT database, as shown in Table 1, the standard deviation of the error of the proposed algorithm are around tolerances accepted by cardiologists. For QRS offset, this new algorithm improves the best published result both in terms of the mean and the STD of detection errors. For QRS onset, the new result is close to the best result which is held by the algorithm EA.

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