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Real-time electrocardiogram P-QRS-T detection–delineation algorithm based on quality-supported analysis of characteristic templates

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ABSTRACT

The main objective of this study is to introduce a simple, low-latency, and accurate algorithm for real-time detection of P-QRS-T waves in the electrocardiogram (ECG) signal. In the proposed method, real-time signal preprocessing, which includes high frequency noise filtering and baseline wander reduction, is performed by applying discrete wavelet transform (DWT). A method based on signal first-order derivative and adaptive threshold adjustment is employed for real-time detection of the QRS complex. Moreover, detection and delineation of P- and T-waves are achieved by correlation analysis conducted between signal and their templates. Besides, signal quality is investigated online, and if the quality of the analysis window is unacceptable, then the algorithm will guess (estimate) the locations of P- and T-waves.

The operating characteristics of the proposed algorithm are evaluated by its implementation to an artificially generated ECG signal whose quality is adjustable from the best (Quality, 100%) to the worst (Quality, $\leq 40\%$) cases based on the random-walk noise theory. The algorithm was applied to the MIT-BIH arrhythmia database, QT database, and Physionet/CinC challenge 2011competition database. The obtained results, which were based on the QT database, showed sensitivity and positive predictivity of Se=99.63% and P+=99.83%, Se=99.83% and P+=99.98%, and Se=99.74% and P+=99.89% for the detection of P-, QRS-, and T-waves, respectively, and the obtained results, which were based on the MIT-BIH arrhythmia database, showed Se=99.81% and P+=99.70% for the detection of the QRS complex. Moreover, it will be shown that the results of the proposed method are reliable for a minimum signal quality value of 70%. According to numerical assessments, 8-ms after the occurrence of R-wave, its location will be identified by the computer code of the proposed algorithm. This parameter is 198-ms and 177-ms for P- and T-waves, respectively.

1. Introduction

The electrocardiogram (ECG) is a simple and non-invasive test for recording the electrical activity of the heart. This signal has three main waves called P, QRS and T, which represent atrial depolarization, ventricular depolarization, and ventricular repolarization, respectively. These waves have significant characteristic features such as occurrence time, amplitude, intervals, and waveform, and several arrhythmias can be diagnosed on the basis of these features. In any application, in which the instantaneous status of the cardiac system must be monitored, one of the important approaches is to record and analyze the ECG signal in real-time mode. For instance, in the ICU, patients with the risk of cardiogenic shock, hypotensive episodes, sudden cardiac arrest,

Abbreviations: DWT, discrete wavelet transform; db, Daubechies wavelet family; ALC, arc length curve; ASC, area under the slope curve; ASC_τ, ASC filtered curve; MSC, mean slope curve; ALC(i^*), amplitude of ALC at the location of the local extremum; $d[n]$, ECG first-order derivative; ASC(i^*), amplitude of ASC at the location of the local extremum; MSC(i^*), amplitude of MSC at the location of the local extremum; A_{QRS}, ASC amplitude at the location of the QRS complex estimated on the basis of beginning of the signal; ALC_m, ALC amplitude average value at the location of R-waves; ASC_m, ASC amplitude average value at the location of R-waves; MSC_m, MSC amplitude average value at the location of R-waves; ALC_R, ALC amplitude at the location of a detected R-wave; ASC_R, ASC amplitude at the location of a detected R-wave; MSC_R, MSC amplitude at the location of a detected R-wave; τ_A, threshold of ASC; C_T, updating waveform template; C_L, waveform template; γ, cross-correlation; C, correlation coefficient; τ^{AL}_{min} and τ^{AL}_{max}, thresholds of acceptable arc length; τ^{N}_{min} and τ^{N}_{max}, thresholds of acceptable number of local extremums; AL_L, arc length of a window of length L; N_{mL}, number of local extremums in a window of length L; T_T, T-wave template; T_{UT}, updated T-wave template; Se, sensitivity; P+, positive predictivity; Sp, specificity; MRT, mean response time; RMSE, root mean square error; QTDB, QT database; MITDB, MIT-BIH arrhythmia database; EECP, enhanced external counter pulsation

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and deep unconsciousness during anesthesia must be continuously monitored by evaluating RR-interval variations, T-wave alternans, P-wave variability, QT interval, and ST-segment elevation level. As another example, in heart rehabilitation systems such as enhanced external counter pulsation, the pneumatic control system receives direct feedback from instantaneous locations of R- and P-waves of the patient, which should be provided by a precise real-time ECG analysis algorithm. On the other hand, in implantable devices such as pacemakers and defibrillators, intercardiac ECG signals should be analyzed in real-time with an algorithm of high accuracy with detection of events conducted with low delay. Therefore, providing a fast and accurate algorithm is helpful for extracting ECG signal features and characteristic events. Until now, various methods have been introduced for the real-time detection of the QRS complex, such as methods based on non-linear transform [1], pattern recognition [2], digital filters and Hilbert transform [3–11], wavelet transform [12–14], QRS complex slope estimation [15], adaptive filters [16], and curve length concept [17]. Furthermore, several proposed methods for the real-time detection of P- and T-waves are established on the basis of P- and T-wave slopes [18], Bayesian inference [19], wavelet transform [20], template matching [21], and threshold-based methods [22].

In several methods of the aforementioned researches, two important parameters of real-time analysis algorithms, i.e., “accuracy” and “algorithm response time”, are not considered simultaneously during the design procedure. In other words, reporting only the accuracy of a real-time ECG analysis algorithm is not sufficient and its response time should be considered during design of the method.

In addition, operating characteristics of an algorithm are strongly dependent on the quality of the processed signal. This means that the quality level of the analyzed signal should be reported for which the accuracy of the method is evaluated. So far, this problem is considered in a few previous studies [23,24].

The main goal of this study is to present a new method to improve the response time without loss of accuracy during noisy conditions. In the proposed method, real-time detection of the QRS complex is conducted by applying signal first-order derivative and adaptive threshold adjustment. According to information theories, decision-making based on multiple criteria significantly reduces the false detection of the QRS complex. Moreover, algorithm response time is enhanced desirably with the replacement of high-delay digital filters by efficient low-latency preprocessing algorithms. Correlation analysis conducted between characteristic templates (P- and T-wave templates) and the ECG signal is applied for the online detection of ECG non-impulsive waves. Besides, the algorithm tests signal quality online, which in low-quality cases can estimate the locations of P- and T-waves on the basis of the previously detected locations of characteristic events. The performance of the proposed method is evaluated by its application to the MIT-BIH arrhythmia database (MITDB) [25], QT database (QTDB) [26,27], and Physionet/CinC challenge 2011 competition database [28]. For evaluation of the performance of the proposed method against reduction of signal quality, the algorithm is tested on the open-source artificially generated ECG signal [29,30], whose quality is adjustable according to the random-walk noise theory.

2. Materials and methods

2.1. Datasets

In this study, for performance evaluation of the proposed algorithm, four ECG databases are used. These databases are (1) the MIT-BIH Arrhythmia Database [25] (48 30-min and two-channel recordings with sampling frequency of 360 Hz), (2) QT Database [26,27] (105 15-min two-channel recordings with sampling frequency of 250 Hz), (3) Physionet/CinC Challenge 2011 [28] (which includes 1500 10-s annotated standard 12-lead ECG recordings with sampling frequency of 500 Hz) and (4) the artificially generated ECG signal [23,29,30] (which includes arbitrary number of quality-variable beats with a tunable sampling frequency). In the third database, the training set is called set “a” (1000 12-lead signals) and the test set is called set “b” (500 12-lead signals). All $1000 \times 12 = 12{,}000$ signals of the training set (set “a”) are put in a new set called “c”).

2.2. General structure

The general block diagram of the proposed method is presented in Fig. 1.

The proposed method has four major steps:

2.2.1. Real-time preprocessing

For every new sample, the last signal window of a specific length is preprocessed by discrete wavelet transform (DWT).In this process, the powerline interference, high frequency noise, and baseline wander are filtered.

2.2.2. Real-time QRS complex detection

With every new sample, three features are extracted on the basis of the signal and its first-order derivative. Next, QRS complexes are detected by devising appropriate decision rules in which required thresholds are tuned adaptively.

2.2.3. Training phase

After gathering data for 60 s, the training phase begins. This phase includes offline analysis procedures. First, all P- and T-waves are detected. Then, all waveforms are clustered and the characteristic templates are generated by implementing ensemble averaging of members in each cluster [31–33].

2.2.4. Test phase

This phase includes online analysis procedures. With every new sample, first, the quality of the last signal window of a specific length is tested. If the quality level is acceptable, then P- and T-waves are delineated by correlation analysis conducted between the signal and their templates. On the other hand, if the quality of the analysis is window is unacceptable, the locations of the P- and T-waves are estimated on the basis of the locations of previously detected P- and T- waves, respectively. It must be noted that the training phase is continued parallel to the test phase so as to generate the ability of self-tuning when new waveforms appear in the signal. In other words, the templates are updated by detecting all new P- and T-waves and if the correlation between the signal and the templates is lower than a specific threshold, a new cluster is generated.

2.3. Real-time preprocessing

DWT is applied for real-time preprocessing of the signal. This transformation has many advantages such as applicability for analysis of non-linear and non-stationary signals such as ECG, acceptable performance even in short-time frames, and low information destruction of the original signal. Daubechies 4 (db. 4) is chosen as the type of the mother wavelet. The original signal is decomposed into 8 levels. First- and second-level detail coefficients and last level approximate coefficients are set to zero to remove high frequency noise and baseline wander effects,