DETECTION OF QRS BOUNDARIES AND T WAVE END IN MULTILEAD ECG SIGNALS

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ABSTRACT

In this paper, we propose a robust multilead electrocardiogram (ECG) detection system based on a continuous wavelet transform (CWT). First of all, QRS complexes are detected. Then, boundaries (onset and end) of each QRS complex are found. In a next step, the T wave peak is detected between the QRS end and the following QRS onset. Finally, the T wave end is found between the peak of T wave and the following QRS onset. These significant points are measured separately in each lead of ECG. Global multilead values are determined from singlelead values by using a selection rule. The proposed algorithm was evaluated on the CSE database. The QRS detector obtained a sensitivity of *Se* = 99.19 % and the T wave detector attained a sensitivity of *Se* = 98.37 %. Standard deviations of differences between program results and database annotations were computed for the QRS onset, the QRS end and the T wave end. Calculated standard deviations were smaller than given accepted tolerances.

1. INTRODUCTION

The automatic detection of significant points in the ECG signal is important to a cardiac disease diagnosis. One of the most important parts of automatic ECG delineation is the QRS detection. Once the positions of QRS complexes are known, the detection of ECG specific points (QRS onset, QRS end, T end, P onset and P end) can follow.

In this paper, the robust multilead QRS onset, QRS end and T wave end detector is proposed. After the QRS detection, boundaries of each QRS complex are found (QRS onset and end). Then, the T wave is localized between two adjacent QRS complexes. Finally, the T wave end is found between the T wave peak and the following QRS complex.

2. METHODS

The designed algorithm is based on a continuous wavelet transform. The wavelet transform at different scales describes the time characteristic of a signal in different frequency bands. While the dyadic wavelet transform (DWT) is restricted to scales that are powers of two (used in [1], [2]), CWT can be evaluated in any real positive scale. This provides us a strong tool for ECG delineation. By choosing optimal scales, we can minimize the influence of noise, artifacts and baseline drift.

The CWT of a time-continuous signal $x(t)$ is defined by the integral

$$CWT\ (b,a) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\psi^* \left(\frac{t-b}{a} \right) dt\,, \qquad (1)$$

where $\psi(t)$ is the wavelet function (mother wavelet), a is the scale parameter and b is the translation parameter.

Some authors used for the wavelet-based ECG delineation the quadratic spline function [1], [2], or the derivative of a Gaussian smoothing function [3], as the prototype wavelet. We tested three biorthogonal wavelets (*bior1.1*, *bior1.3* and *bior1.5*). The best results were achieved by using the *bior1.5* function. There is also a difference in a used scale approach. While authors in [1], [2] used the multiscale approach, in this work the singlescale approach was applied. The scale 15 was found as the optimal common scale for detection of the QRS onset and the QRS end. This scale is however not appropriate for determination of the T wave end. The scale 41 was found as the optimal scale for the T wave end detection. In Fig. 1 are shown magnitude spectra of corresponding wavelet functions (left) and the wavelet *bior1.5* (right) at scales 15 and 41.

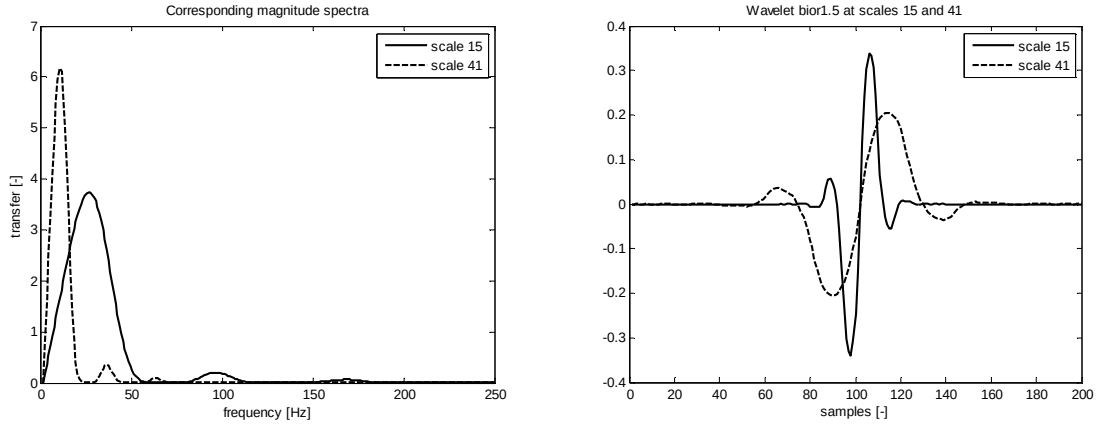

Figure 1: Corresponding magnitude spectra (left) and wavelets *bior1.5* (right) at the specific scales 15 and 41.

2.1. DETECTION OF QRS, QRS ONSET AND QRS END

In literature [4], we can find many different QRS detection algorithms. The highest performance have algorithms based on amplitude and slope thresholding or digital filtering. The wavelet-based QRS detector and delineator, proposed in this paper, is using advantages of those algorithms.

Regarding the selected prototype wavelet, zero-crossings of the CWT correspond to the local maxima of the signal modulus and the local maxima of the CWT modulus correspond to maximum slopes in the signal.

In the first step, the algorithm searches for pairs of modulus maxima exceeding threshold ξ_{QRS} in the scale 15. The QRS complex is found as a zero-crossing between the pair maximum-minimum, or minimum-maximum. This way can be detected waves Q, R and S (one of them, two, or even all) within the QRS complex, but only the first one is marked as the QRS complex. It is obvious, that in most cases the R wave is found, but not always. QRS complexes of different ECG signals have generally different morphology.

In the next step, the detector begins from the positions marked as the QRS complex and tests, whether the modulus maximum between two adjacent zero-crossings is larger than the threshold ξ_{QRSon} (ξ_{QRSend}). In the case, that is larger, the algorithm tests the modulus maximum between the previous (next) pair of zero-crossings. Once the modulus maximum does not exceed the threshold ξ_{QRSon} (ξ_{QRSend}), the QRS onset (end) is localized between the previous tested pair of zero-crossings. The QRS onset (end) is marked as the first (last) sample exceeding (in absolute value) the threshold ξ_{QRSon} (ξ_{QRSend}).

Results of the QRS onset and end detection on two segments of two different ECG signals from the lead I are shown in Fig. 2.

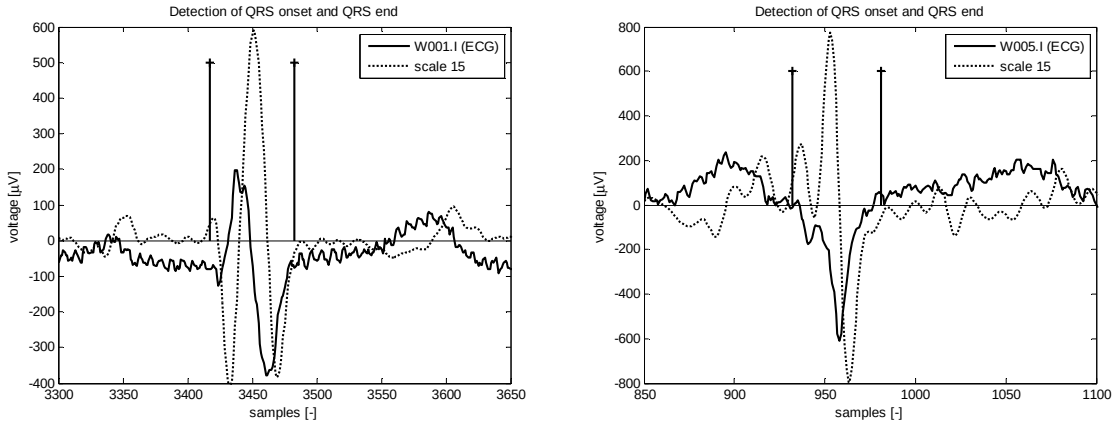

Figure 2: Detection of the QRS onset and the QRS end at the scale 15.

2.2. DETECTION OF T WAVE AND T WAVE END

Detection of the T wave end is probably the most complicated part of the ECG delineation. First of all, the T wave itself must be detected. According to [2], the T wave can have several morphologies: positive, negative, biphasic, only upwards or only downwards. The proposed T wave detector is capable of detect any of mentioned morphologies.

In the first step, the algorithm searches in the scale 41 between the QRS end and the following QRS onset for pairs of modulus maxima exceeding the threshold ξ_T. The T wave is found as a zero-crossing between the pair maximum-minimum, or minimum-maximum. More than one wave can be detected this way between two adjacent QRS complexes, but only the first one is marked as the T wave.

In the next step, the delineation algorithm begins from the positions (zeros) given by the T wave detector. The delineator is testing, whether the modulus maximum between two adjacent zero-crossings is larger than the threshold ξ_{Tend}. If it is larger, than the algorithm is testing the modulus maximum between another two adjacent zero-crossings. Once the modulus maximum is smaller than the threshold ξ_{Tend}, the T wave end is found between the previous tested pair of zero-crossings. The T wave end is determined as the last sample larger (in absolute value) than the threshold ξ_{Tend}.

Results of the T wave end detection on two segments of two different ECG signals from the lead I are shown in Fig. 3.

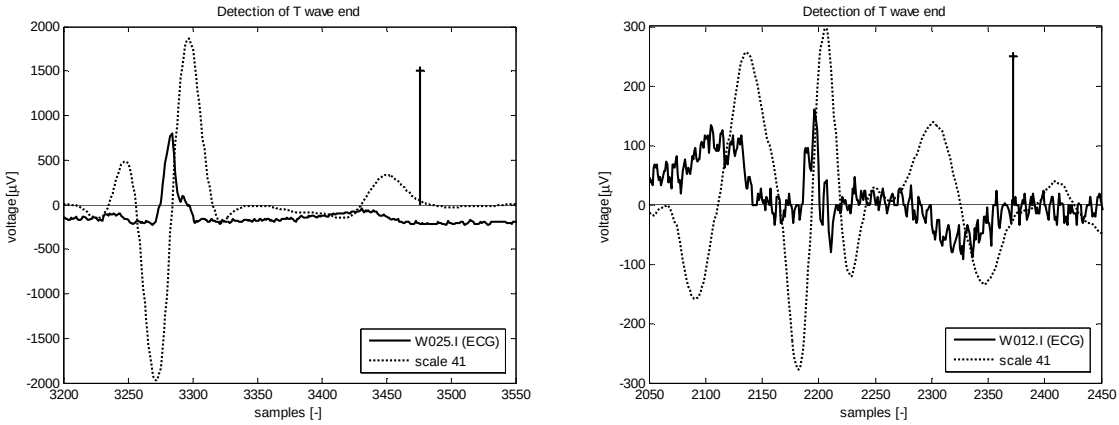

Figure 3: Detection of the T wave end at the scale 41.

3. RESULTS

The proposed ECG delineator was evaluated on the CSE database. Sampling frequency of ECG signals from this database is 500 Hz. The CSE multilead measurement database (CSEDB) contains of 125 annotated ECG signals. The CSEDB signals include 12 standard leads and Frank leads. Our delineator was evaluated on 12 standard leads for 123 ECG signals. Signals W067 and W070 were skipped, because annotations for the QRS onset and end were missing.

While the database annotations are common for all leads, the designed program is processing each of 12 leads separately. The global value for comparison with CSEDB annotations is gained as one of those individual positions by using special selection/sorting algorithm.

To asses the designed QRS and T wave detector we calculated the sensitivity *Se* given by equation

$$Se = TP/(TP + FN), \qquad (2)$$

where *TP* is the number of true positive detections and *FN* is the number of false negative detections. The QRS detector obtained a sensitivity of *Se* = 99.19 % and the T wave detector attained a sensitivity of *Se* = 98.37 %.

Standard deviations *s* of differences between program results and database annotations were computed for the QRS onset, the QRS end and the T wave end. The results are given in Tab 1,

Significant point	m ± s (ms)	Tolerances $2s_{CSE}$ (ms)
QRS onset	0.4 ± 4.0	6.5
QRS end	-0.3 ± 5.0	11.6
T wave end	2.0 ± 12.4	30.6

Table 1: Evaluation results of the proposed ECG delineator on the CSE database.

where *m* is the mean deviation between program results and database annotations, *s* is the standard deviation and $2s_{CSE}$ are delineation error tolerances, given in [5].

4. DISCUSSION

We considered the delineation error tolerances given by the CSE Working Party in [5] as a reference. The tolerances defined in [5] are given in a form of two standard deviations. Some authors [2], [3] considered, that an algorithm should accomplish $s < 2s_{CSE}$ (the loose criterion), while some others considered, that $s < s_{CSE}$ should be accomplished (the strict criterion).

The proposed ECG delineator accomplished the loose criterion for all three significant points and the strict criterion for the QRS end and the T wave end. The wavelet transform approach proposed in [2] accomplished the loose criteria, but did not accomplish the strict criteria. Other wavelet-based approach proposed in [3] accomplished the strict criterion for the QRS onset and the QRS end, but only the loose criterion for the T wave end.

5. CONCLUSION

The proposed ECG delineation algorithm did well in comparison with others mentioned algorithms. The delineator accomplished the strict criterion in two of three cases and the loose criterion in all cases. The most significant improvement was found in the T wave end detection. The T wave end is the most difficult ECG point to detect and any of the mentioned algorithms did not accomplish the strict criteria for this point. Our algorithm accomplished the strict criterion for the T wave end detection. Because of the singlescale approach the proposed ECG delineator is extremely fast and simple. The delineator proposed in this paper appears to be robust and effective tool for the ECG delineation.

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