A WAVELET-BASED QT INTERVAL DETECTION IN ISOLATED RABBIT HEART ECG SIGNALS

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Abstract: In this work, we present a method of automatic detection of QT interval in isolated rabbit heart ECG signals. The method is based on continuous wavelet transform and uses linear classification approach in T wave detection. The algorithm was tested on real experimental data with manually annotated beats and showed good performance in both accuracy and detection sensitivity.

Keywords: QT interval, detection, wavelet transform, isolated rabbit heart, ECG

1. INTRODUCTION

Measurements of QT interval provide fundamental information about cardiac repolarization and are routinely used in clinical medicine often realized manually or by semi-automatic algorithms. Accurate detection of QT interval is thus important in diagnosis and research of repolarization disorders. Common methods in human QT detection use wavelet transform [1][2][3], digital filtering and derivative approaches [4], possibly combined with other methods based on various types of line fitting [5],[6]. Isolated hearts from small animals, such as rabbits or rats, are often used in experimental research. Such ECG recordings have often long term duration which makes automatic QT detection an important and useful tool.

In this paper, we present a continuous wavelet-based method to detect the onset of QRS complexes and the offset of T waves in rabbit ECG signals. We adjusted algorithm settings according to known properties of rabbit ECG signals. Algorithm performance is evaluated on our own set of experimental data with manually annotated reference points.

2. MATERIALS AND METHODS

Experimental electrograms were obtained by measuring on isolated New Zealand rabbit hearts. Hearts were perfused according to Langendorff at a constant pressure of 80 mmHg by an oxygenated (95% O_2; 5% CO_2) Krebs-Henseleit buffer. Heart function was stabilized for 15–20 minutes. Experimental protocol was then followed consisting of three general ischemia and reperfusion phases, repeated alternately. Total of 14 individual ECG recordings were obtained lasting each 152 min. in average. Average heart beat attains 121±40 BPM with minimum and maximum of 17 BPM and 271 BPM, respectively. QT interval length in 217 randomly selected heart cycles was (in ms) 211±28 (range: 157–303). Average QRS complex length was 35±9 ms (range: 23–70).

Data were acquired by National Instruments USB-6259 measuring card using 16 bit resolution and sampling rate f_s = 2000 Hz. Tree Ag-AgCl electrodes placed in an orthogonal coordinates X, Y and Z were used.

Power spectral densities of rabbit ECG waveforms are depicted in Figure 1. Estimation was performed using averaged periodogram of 24 realizations of a signal.

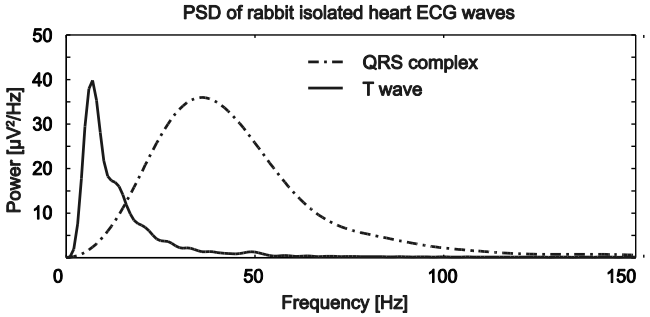

Figure 1: Power spectral density of QRS complex and T wave in isolated rabbit heart ECG signals.

2.1. WAVELET BASED APPROACH

The wavelet transform (WT) can be described as a time-scale representation of a signal decomposed to various frequency bands using a set of basis functions.

Time-continuous wavelet transform (CWT) of a signal $x(t)$ is defined as integral function:

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

where a and b is a parameter of dilatation and translation, respectively, of complex conjugate mother wavelet Ψ^*. By increasing the scale factor a, lower frequency components are represented in transformed signal. Discrete dyadic transform (DWT) with scale factor $a = 2^n$; $n \in Z^+$ is typically used [1],[2]. However, using CWT in rabbit ECG signals appears to be more appropriate due to the possibility of accurate scale selection and better distinguishing of waveforms, artifacts and noise.

Prototype wavelets used in this paper are shown in Figure 2 including its magnitude spectra at chosen scales. We found the 1st derivative of Gaussian smoothing function $\Psi_1(t)$ to be the best in T wave offset detection, while the 3rd derivative of Gaussian $\Psi_2(t)$ function gives better results in QRS complex and QRS onset detection. Both prototype wavelets are designed as smooth anti-symmetric functions. Local extremes of the signal thus correspond to zero-crossings of the CWT and the rising slope is related to the local minima in transformed signal and vice versa [3].

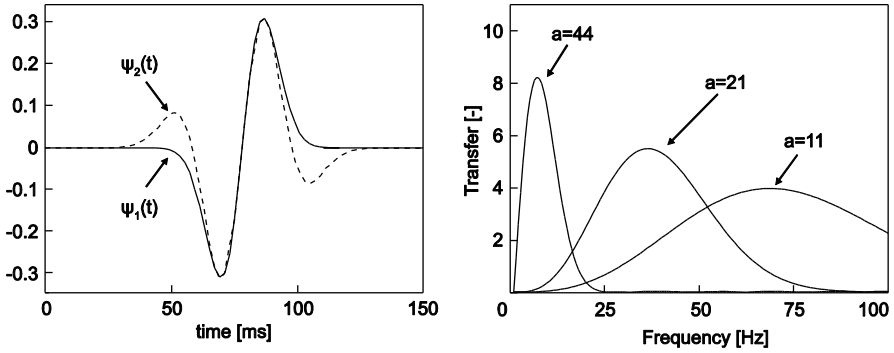

Figure 2: Prototype wavelet $\Psi_1(t)$ and $\Psi_2(t)$ and its magnitude spectra at chosen scales a. Scale 21 and 11 are related to wavelet $\Psi_2(t)$ and scale 44 to wavelet $\Psi_1(t)$.

2.2. ALGORITHM DESCRIPTION

Proposed algorithm consists of three phases: detection of QRS complex, delineation of the QRS complex onset and detection and delineation of T wave offset. The algorithm is based on a single lead basis and uses multilead rule to calculate more accurate global positions.

Scales of CWT were chosen so that maximum energy of analyzed wave and corresponding scale are within the same position in spectral domain. Most of the energy of QRS complex lies between 18 and 60 Hz with its maximum at 38 Hz. This corresponds to scale 21 at sampling rate f_s = 2000 Hz. At about 70 Hz there are still significant energy components of high frequency waves of the complex and thus choosing scale 11 appears to be the most relevant. Similarly, scale 44 was chosen with respect to the highest energy of T wave at 9 Hz.

QRS detection

In the first step, the algorithm searches for two extremes with opposite polarity in scale 21 that exceed threshold ξ_{QRS}. If corresponding extremes above threshold are also found in scale 11, QRS complex is considered to be present. Threshold is computed separately for each scale from the 10 second segment of a signal using statistical properties of the wavelet coefficients distribution as:

$$\xi_{QRS} = \varepsilon_{\mathrm{QRS}}\mathrm{Median}[P_h - (\beta_c + P_l)], \tag{2}$$

$$\beta_c = \frac{\mu^4}{\sigma^4}\varepsilon_c, \tag{3}$$

where P_h and P_l determines higher and lower limit of inter-percentile range. Lower percentile is adapted by the fourth standardized moment of CWT coefficients distribution. Multiplying constant ε_c and ε_{QRS} is obtained empirically.

Position of QRS complex is given by zero-crossing between corresponding negative-positive pair of extremes, if present. False detections are reduced by applying timing rules, e.g., limited distance between two consecutive extremes, limited width of detected peak and refractory time, where all possible detections are excluded.

QRS onset detection

Onset of the QRS complex is detected at scale 11. Initial onset location is set to the zero-crossing in scale 11 related to QRS position detected in previous step. In each step, peak value between actual onset location and preceding zero-crossing is checked. If such extreme is above threshold ξ_q, new onset position is translocated to earlier zero-crossing. Threshold is calculated as a standard deviation of given segment of transformed signal around QRS complex multiplied by constant 0.25. Algorithm stops searching if subliminal extreme occurs and neither further extreme is larger than ξ_q.

Exact location of the onset of QRS complex is then determined by the position of the first sample below threshold $\xi_{QRSon} = 0.25\xi_q$ between last accepted onset position represented by zero-crossing and following immediate extreme.

T wave offset detection

T wave is detected at scale 44 in beat-rate-dependent time window set after QRS complex. Classification function φ is used to determine possible extremes in transformed signal belonging to T wave. Mono and biphasic waves thus can be detected as well as ischemic waveforms overlaid by ST elevation. The function is linear, defined by following formula:

$$\varphi_{(i:i+1)} = p_p\left(w_1\sum_{i}^{i+1} p_{m_i} + w_2\sum_{i}^{i+1} p_{w_i} + w_3 p_{d_{(i:i+1)}}\right). \tag{4}$$

In equation above, p_m denotes peak voltage level, p_w and p_d is a distance from peak to the center of time window and peak to peak, respectively. Parameter p_p is binary coefficient in sense of mutual polarity of consecutive peaks taking value -1 (positive-positive pair) or 1 (positive-negative pair). Weighting coefficients w_1=1.6; w_2=0.85 and w_3=1.25 are empirical constants.

Pair of extremes with the greatest functional value $\varphi_{(i:i+1)}$ is considered to be a part of detected waveform. T wave offset is marked at position of the first sample below threshold ξ_{Toff} following the last detected extreme. Threshold ξ_{Toff} is given by value of the largest extreme multiplied by 0.4.

Examples of detected QT intervals obtained by algorithm described above are shown in Figure 3. Transformed signals at scale 44 are also included.

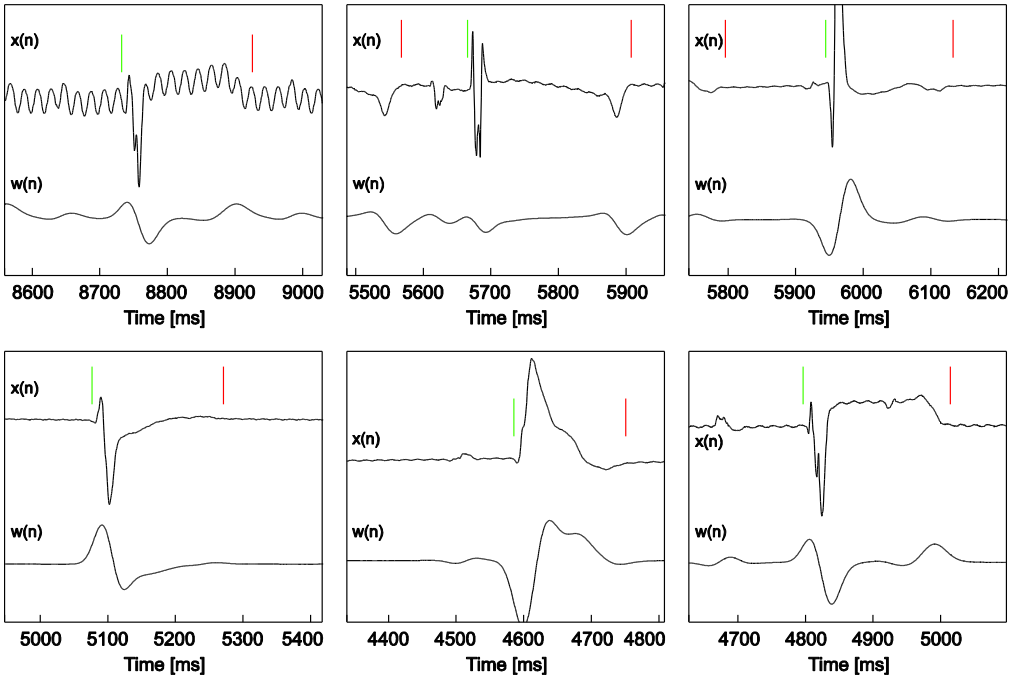

Figure 3: Examples of QT interval detection in isolated rabbit heart ECG signal; x(n) – original signal, w(n) – transformed signal at scale 44

3. RESULTS

Proposed algorithm was tested on subset of all recordings consisting of 258 randomly selected segments within one randomly selected and manually annotated ECG cycle in each signal. Average error between global detected positions and references (μ) and standard deviation of all errors (σ) was calculated for both global and local positions. Sensitivity of the detection is calculated as TP/(TP+FN), where TP is amount of true positive detections and FN is number of false negative detections.

Overall results are shown in Table 1. Since there are no known error limits, we included those published by [7], which reflects variations between cardiologist measurements in human ECG. As it can be seen, both single lead and multi lead detections meet given criterions in all cases. Global detection obtained less error by 1ms in QRS onset and by 2 ms in T wave offset in comparison with local detection. Using multilead rule also highly improved reached value of sensitivity. Distribution of measured global errors can be seen in Figure 4.

	QRS onset μ±σ [ms]	T offset μ±σ [ms]
Local	-2.5±5.5 (Se=97.89%)	-0.4±16.2 (Se=91.6%)
Global	-2.7±4.1 (Se=100%)	0.1±14.4 (Se=98.85%)
$2S_{CSE}$ limits	not defined ± 6.5	not defined ± 30.6

Table 1: The results of QT detector obtained by single lead and multi lead approach.

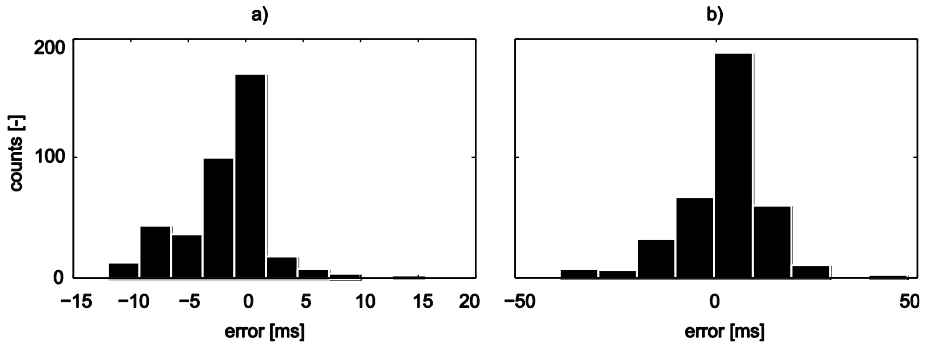

Figure 4: Histogram of the errors between global positions and references: a) QRS onset; b) T offset

4. CONCLUSION

In this paper, we have presented a method for QT interval detection in isolated rabbit heart ECG signals based on continuous wavelet transform. Algorithm was evaluated on real experimental data with manually annotated reference points. Method is robust against noise, artifacts and presence of ST interval changes caused by general ischemia. Global version of the algorithm can detect QRS onset and T wave offset with high values of sensitivity; 100% and 98.85%, respectively. Also, there is significant improvement in measured errors by using global positions instead of local. Obtained errors fulfilled given limits and are comparable to those reached in human QT detection. However, relation between accepted errors and dissimilar length of waves in rabbit and human ECG must be considered.

ACKNOWLEDGEMENT

This work was supported by the grant project of the Grant Agency GAČR P102/12/2034.

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