Signal processing methods for ST variability assessment in ECG

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Abstract - The beat-to-beat ST variability in the ECG signal is becoming an important indicator in neurocardiology. However, accurate determination of the ST variability is difficult because of uncertainty in the determination of the end point of the ST interval. T waves change their form because of breathing, heart movements, changing of lead positions etc. If the ST variability is small, as in most neurological patients, their reliable assessment is even more difficult. In this paper, we propose two methods for the assessment of the ST variability: the beat-to-beat variability of the RT interval (the time between the peak of the R wave and the peak of the T wave) and the TTs interval (the time between the peak of the T wave and the T wave point with maximal negative slope). The paper elaborates in details the method for the determination of Ts. The method is analyzed through its noise sensitivity estimation.

I. INTRODUCTION

Electrocardiogram (ECG) is a diagnostic tool in cardiology that monitors the electrical heart activity on the body surface resulting from differences induced by action potentials of the cells in the muscular tissue of the heart. Every phase of heart activity cycle or cardiac cycle (or known as heartbeat) results in a separate waveform in the ECG (Fig. 1a). These waves are result of non-homogeneities of action potentials throughout the heart, related to the start-time of depolarization and the time-course of the action potential in each cell. The waves Q, R and S are manifestation of the depolarization in the two ventricles, while the waves T and U are consequence of the repolarization process in the ventricles. Large differences of action potential courses during repolarization (dispersion of repolarization) can lead to arrhythmias, especially when these differences arise at small distances. Whether the dispersion is present at small distance through the heart muscle wall (transmural dispersion), from base-to-apex, or from one ventricle to the other ventricle, has been a subject of long on-going debate [1, 2].

The repolarization variability in the heart can be measured with the variability of the ST interval defined between the J point (the point at which the QRS complex finishes) and the end of the T wave (Fig. 1a). The ST variability has been assessed with different methods in previous studies [3-7]. As the start of the ST interval (the J point) is not well defined, replacement intervals are often used in assessing the beat-to-beat variability of the repolarization i.e. the interval between the peak of the R wave and the peak of the T wave (RT interval) complemented with the interval from the peak of the T wave to the end of the T wave [3-5]. R waves are used instead of S waves, because the difference between the R and the S peaks is typically small (< 50 ms) and constant. Moreover, R peaks are present on all ECGs with clearly defined peaks. The ST interval can be obtained from the RT interval by subtracting the (S-peak - R-peak) time determined separately. Unfortunately, the end of the T-wave is not a well-defined instant, and, in addition, the presence of a U-wave can further complicate the determination of a ST interval, according to the definition given in [6].

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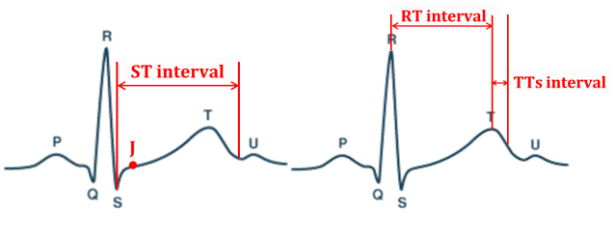
In our previous study [7] we have presented a method for the determination of the RT variability. In this paper, we present additional method to complement the one in [7] in ST variability assessment. So, the two methods that we propose for the assessment of the ST variability are: the beat-to-beat variability of the RT interval and beat-to-beat variability of the TTs interval (Fig. 1b). The second interval, TTs, is defined as the interval between the peak of the T wave and the T wave point with maximal negative slope. The paper elaborates the method for the determination of the maximal negative slope on the T wave through its noise sensitivity estimation. Additionally, it presents the results for the TTs variability of a measured ECG signal for selected cases of healthy subject and HTX subject (patient with transplanted heart).

II. METHODS

The RT and TTs intervals are defined with three points on the ECG signal: the R peak, the T peak and the maximal negative slope on the T wave. The methods for determination of these points are developed and integrated into a custom software, named NeuroECG, for analysis of biomedical signals (like ECG, breathing). NeuroECG incorporates also a measurement module developed for on-line recording of biomedical signals. There are two types of data streams (channels) in NeuroECG:



(a) (b)

Figure 1. (a) ECG waveforms with marked ST interval. (b) Marked RT and TTs intervals for the assesment of the ST interval.

- Measured (continuous) channels like ECG, blood pressure, breathing, characterized by sampling rate. In particular, the ECG measurements that we work with are with high resolution (1000 – 1800 Hz) and duration of 520 seconds.

- Event channels, an innovative approach of NeuroECG, which enable a more abstract view on the analysis of biomedical signals. An event channel is generated from a measured channel based on different events. The events that we are interested in: the R peak, the T peak and the maximal negative slope on the T wave, are generated from the ECG measured channel. Each event channel is characterized by its time and value. For example, in determination of the R peak, the time of each event in the channel is the time when R peak is determined, and the value is the distance in time to the previous R peak.

What we have added is an integrated procedure build in NeuroECG which determines all important T-wave times automatically, i.e. three event channels with T-time (maximal T-wave amplitude), Ts-time (maximal negative slope), and Te-time (intersection of the maximal negative slope line with the baseline).

The methods for determination of the R peak and the T peak have been described and evaluated in [7]. Following in this section is the description of the method for determination of the maximal negative slope on the T wave.

A. Method for determination of the maximal negative T wave slope

The method for determination of the maximal negative T wave slope is graphically presented in Fig. 2 on a T-wave retrieved with down sampling of a real ECG signal. We show every 10-th sample to obtain a hypothetical sampling rate of 100 Hz for easier description of the proposed method. Before applying the method, a baseline correction and a low pass filtering is performed. These pre-steps are integrated in the procedure and are not analyzed in this paper.

The main approach that we use in the method is to perform linear least squares approximation between a point and its +/- N neighbors, determine the slope of the approximation line in each point, and assign the value of the slope to the point.

The parameters that this procedure takes as an input are:

- The minimal and maximal RT time (default: 0.1 s, 0.45 s),

- The number of neighboring points N for the approximation to determine the T-wave maximal negative slope,

- The frequency of the low pass filter (in Hz).

For demonstration purpose, we have set the number of neighboring points N to +/- 2. So, for each point and its left and right 2 neighbors, we perform a linear least squares approximation and determine the slope, i.e. the derivative of the approximation line as the ratio between delta (y) and delta (t). After we perform the same step for all points, we get the discrete derivative (Fig. 2a). Next, we find the minimal amplitude among the derivative points (approximate Ts point) and its two neighboring points (Fig. 2b). Then, we improve the resolution with quadratic interpolation using these tree points. Finally, we determine the minimum on the interpolation curve and declare that point as a point with the maximal negative slope (Fig. 2c).

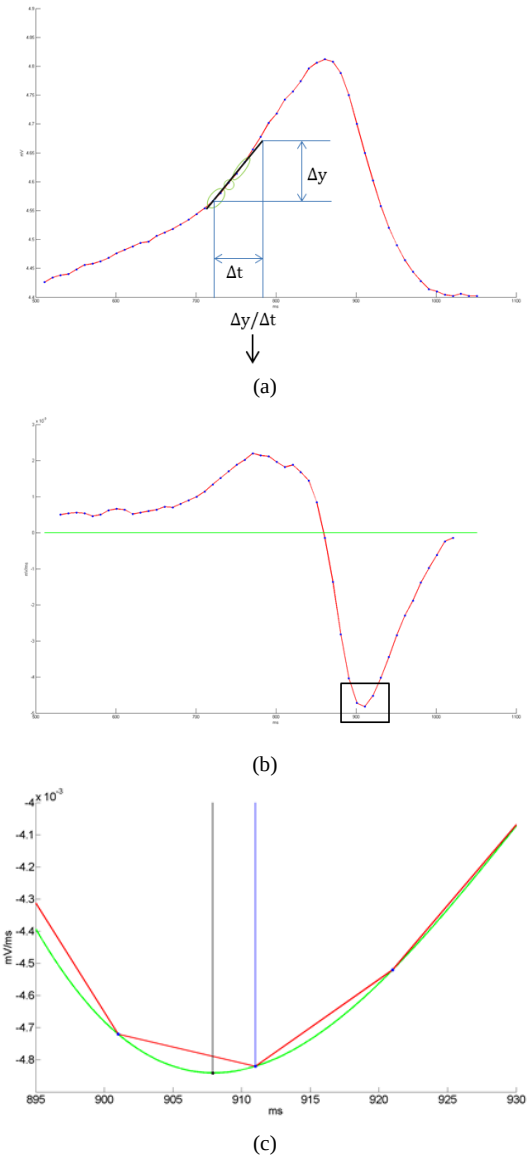


Figure 2. Graphical representation of the method for the determenation of the maximal negative slope on the T wave. (a) Downsampled T-wave from a real ECG (sampling rate 100 Hz) and the least squares approximation procedure for determinating the slope of the approximation line. (b) Discrete derivative curve (red). (c) Approximate Ts point (blue line) and quadratic interpolation (green) of the discrete derivative for improving the resolution of the Ts time (black line).

B. *Noise sensitivity estimation of the methods*

To estimate the noise sensitivity of the method for determination of the maximal negative slope on the T wave, we define an artificial T-wave as an asymmetric slope cosine function [8]. The artificial T-wave is defined as a function of time with the following equation:

$$T=\frac{\cos(\pi(t/a))+1}{2}\quad\begin{array}{lll} a=0.16 & for & -0.16<t<0 \\ a=0.08 & for & 0\le t<0.08 \\ T=0 & for & 0.08\le t\le -0.16 \end{array} \qquad (1)$$

For the artificial simulated T-wave we can analytically determine the Ts points and use it for evaluating the timing error after we add noise to the signal and apply the method.

We tested two types of noise:

- Gaussian noise with signal-to-noise ratio (SNR) ranging from 1 to 150. For each SNR, 100 runs were performed. The SD of the timing errors and its maximal value were calculated.

- Sinusoidal noise with frequency in the range from 0 to 100 Hz, and amplitude 10%, 1% and 0.1% of the one of the simulated T-wave (equivalent to SNR of 20, 40 and 60 dB, respectively). After 100 simulation runs on a single frequency, the SD of the timing errors and its maximal value were calculated. In each simulation run, only the sinusoid phase was changed randomly.

Following our previous analysis, the parameter N (neighboring points for the least squares approximation) was set to 20 and the frequency of the low pass filter to 40 Hz.

III. Results and Discussion

A. *Noise sensitivity estimation results*

The dependence of the timing error on the SNR when the T wave is disturbed with Gaussian noise is shown in Fig. 3. With improved SNR, the timing errors become smaller. For SNR greater than approximately 40 dB, the timing error becomes less than 1 ms. Great disturbances can be observed for lower SNR, indicating instability of the method for low SNR values.

The dependence of the resulting timing error on the frequency of a disturbing sinusoidal noise is shown in Fig. 4. Local minimums can be observed at particular frequencies. This result can be beneficial when selecting the parameters of the method (the N parameter and the frequency of the low pass filter). Large timing errors can be observed for low frequency noises for smaller SNR; however, for larger SNR, the error for low frequency noises becomes smaller (even smaller than 1 ms for SNR of 60 dB). The timing error becomes low for high frequency noises (> 60 Hz).

Compared to the results for the noise sensitivity of the method for determination of the T peak in [7], the method for the determination of the Ts point is more sensitive to noise than the one for T peak.

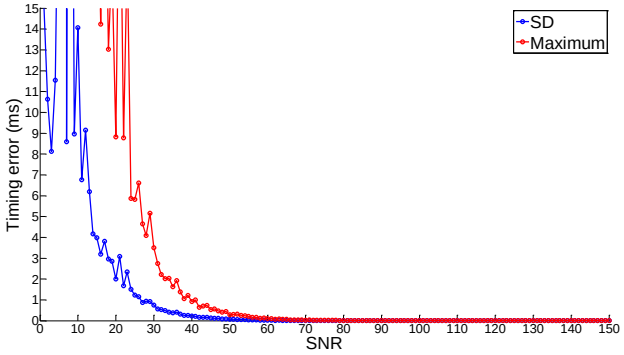
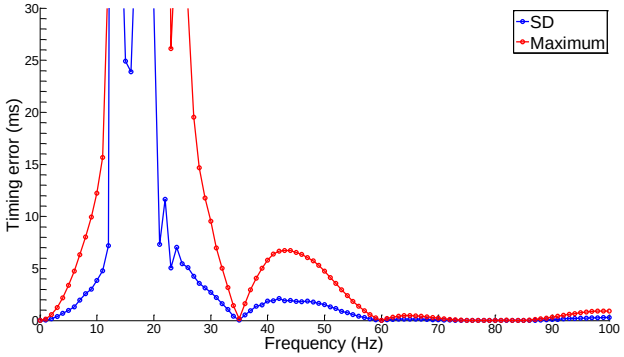
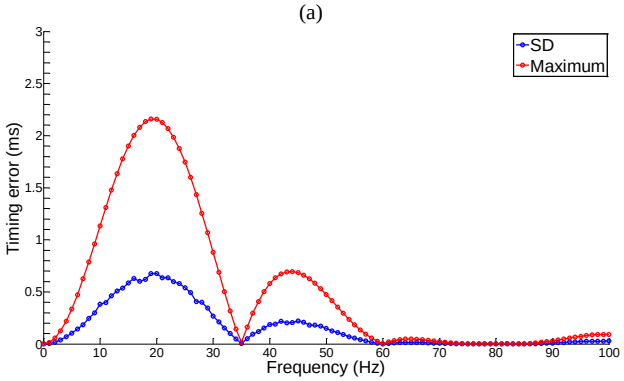


Figure 3. Timing error of the method for the determination of the maximal negative slope on the T wave as a function of the signal-to-noise ratio (SNR) when disturbed with Gaussian noise.



(a)



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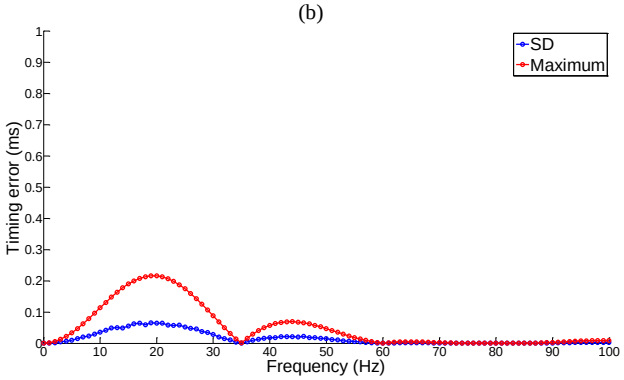
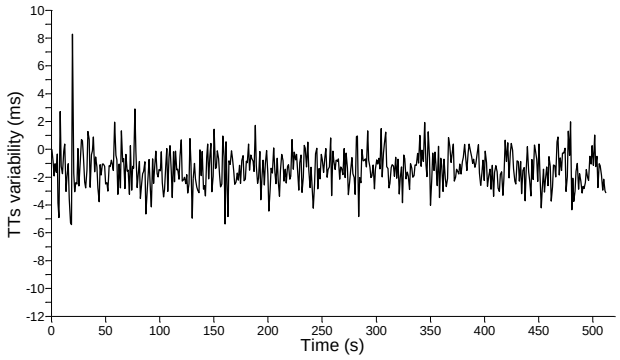
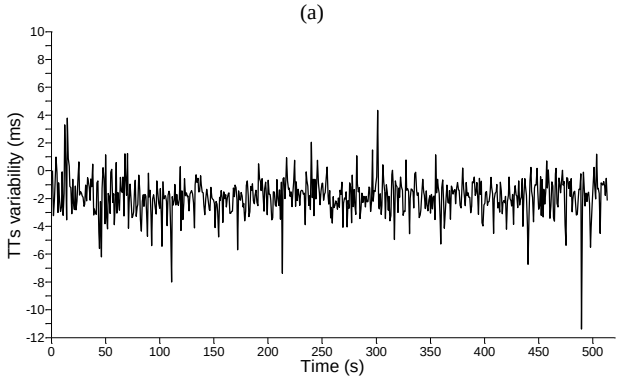


(c)

Figure 4. Timing error of the method for the determination of the maximal negative slope on the T wave as a function of the frequency of a disturbing sinusoidal noise with amplitude (a) 10% of the T wave amplitude, equivalent to SNR = 20 dB. (b) 1% of the T wave amplitude, equivalent to SNR = 40 dB. (c) 0.1% of the T wave amplitude, equivalent to SNR = 60 dB.



(a)



(b)

Figure 5. TTs variability for a selected case of (a) Healthy subject. After linear detrend of the TTs data, the TTs variability is 1.4 ± 1.4 ms. (b) HTX subject (patient with translanted hearth). After linear detrend of the TTs data, the TTs variability is 1.9 ± 1.4 ms.

B. Measured TTs variability

Using the method for determination of the maximal negative slope on the T wave, we calculated the TTs variability for selected cases of a healthy subject and a HTX subject (patient with transplanted heart). The results are shown in Fig. 5. We measured TTs variability of 1.4 ± 1.4 ms for the health subject and TTs variability of 1.9 ± 1.4 ms for the HTX patient. The TTs variability for the case of a healthy subject is in the same range as the QT variability measured in [7].

The SNR for high frequency noise, before assessment of the TTs variability (after filtering), was > 50 dB for both cases. Low frequency noise, after the removal of base line wondering, had frequencies < 1Hz and consequently, according to the noise sensitivity estimation results, the timing errors was small. For both cases, the low frequency noise was < 10%.

IV. CONLUSION

In this study, we have demonstrated a method for determination of a characteristic point on the T wave that can further complement the assessment of the beat-to-beat repolarization variability: the maximal negative slope on the T wave.

We have analyzed the method through its sensitivity on a Gaussian and sinusoidal noise. The results show that for sufficient SNR, the timing errors of the method are small enough. Large timing error is expected in low frequency noises (movement artifacts). The results for the measured variability of the interval between the peak of the T wave and the point on the T wave with the maximal negative slope (TTs interval) in two selected cases of a healthy subject and a HTX patient show that the TTs variability in those cases is in the same range. Clinical discussion of this result would be a subject of further work. Moreover, a study of the TTs variability in a group of health subjects and a group of HTX patients is also planned as future work. The study will assess the TTs variability in these groups, and, furthermore, eventual coherence with breathing/RT interval will be determined.

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