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Improved ECG pre-processing for beat-to-beat QT interval variability measurement

Muhammad A. Hasan, *Student Member, IEEE*, Vito Starc, Alberto Porta, *Member, IEEE,* Derek Abbott, *Fellow, IEEE*, and Mathias Baumert, *Member, IEEE*

Abstract—**The aim of this study was to enhance the ECG pre-processing modalities for beat-to-beat QT interval variability measurement based on template matching. The R-peak detection algorithm has been substituted and an efficient baseline removal algorithm has been implemented in existing computer software. To test performance we used simulated ECG data with fixed QT intervals featuring Gaussian noise, baseline wander and amplitude modulation and two alternative algorithms. We computed the standard deviation of beat-to-beat QT intervals as a marker of QT interval variability (QTV). Significantly a lower beat-to-beat QTV was found in the updated approach compared the original algorithm. In addition, the updated template matching computer software outperformed the previous version in discarding fewer beats. In conclusion, the updated ECG preprocessing algorithm is recommended for more accurate quantification of beat-to-beat QT interval variability.**

I. Introduction

The duration of the QT interval represents the total time of ventricular depolarization and repolarization of a cardiac cycle in ECG. The quantification of beat-to-beat QTV has received significant interest for investigating repolarization abnormalities in patients with different cardiac conditions [1-3]. Importantly, elevated beat-to-beat QTV has also been identified as a marker of increased risk for sudden cardiac death [4-6]. Beat-to-beat QTV measurements from standard 12-lead ECGs showed significant differences between leads [7, 8]. Beat-to-beat variability in the QT segment can also be analysed using a vectorcardiographic (VCG) approach, which has shown diagnostic capabilities for identifying cardiac patients [9-11].

The existing measurement techniques for beat-to-beat QT interval in surface ECG are limited in their accuracy due to different reasons. Generally, the first task to be considered for accurate quantification of beat-to-beat QTV is the accurate R-peak detection followed by the detection of Q-wave onset and T-wave offset. If the R-peak detection is faulty then the whole quantification of QTV will be affected. Baseline wander is one of the noises that causes problems for detecting the R-peaks of surface ECG. Due to the baseline wander, the T-peak could be higher than the R-peak and detected as an R-peak instead. In addition, it may also affect the detection of the T-wave offset and thereby affect the measurement of QTV.

The real time QRS detection algorithm proposed by Pan & Tompkins [12] is widely used and also implemented in the computer software for beat-to-beat QT measurements developed by Berger and his co-workers [13]. However, a number of studies have investigated the accuracy of Pan & Tompkins' QRS detection algorithm and indicate difficulties when detecting QRS complexes in ECG complicated by cardiac disorders or arrhythmia. In particular, most of the studies reported miss- and false detection of true R-peak with less effective baseline removal in ECG signal [14-20].

Therefore, in this study, we incorporated an alternative R-peak detection technique and baseline removal approach in the existing computer software, which was developed by Berger and his co-workers [13]. The performance of the updated approach has been compared with the existing method [13] and two other methods (conventional method [21], template time shift method [22]) on simulated ECG as described in a previous article [23].

II. Methods and Methodology

A. Data

In this study, we considered the same simulated ECG data that was reported in an earlier article [23]. In brief, the original ECG (a normal noise-free cardiac cycle) was obtained from lead II with sampling frequency 1000 Hz and then digitized (12 bit resolution) using an A/D board. Ten cardiac beats were computed from the original one by decreasing T-wave amplitudes by factor k from 1.0 to 0.1 (where k = 1.0 represents the original cardiac cycle). Finally, ten synthetic signals with 500 cardiac cycles were obtained by repeating each of the ten beats 500 times. All ECG are characterized by no variability in heart period and ventricular repolarization duration.

B. ECG pre-processing

The ECG pre-processing stage of the QT variability analysis software was updated in two major aspects to improve the overall performance for the quantification of beat-to-beat QT interval variability [13].

Firstly, a robust R-peak detection (automated R-peak finding logic) algorithm has been used to substitute the R-peak detection algorithm, which was based on the algorithm that was proposed by Pan and Tompkins [12]. Secondly, a

M. A. Hasan, D. Abbott and M. Baumert are with the Centre for Biomedical Engineering (CBME) and the School of Electrical & Electronic Engineering, University of Adelaide, SA 5005, Australia (phone: 61-8-8313-4115; fax: 61-8-8303-4360; e-mail: muhammad.hasan@adelaide.edu.au, dabbott@eleceng.adelaide.edu.au mathias.baumert@adelaide.edu.au).

A. Porta is with the Department of Biomedical Sciences for Health, University of Milan, Milan 20122, Italy (e-mail: alberto.porta@unimi.it)

V. Starc is with the School of Medicine, The University of Ljubljana, 1000 Ljubljana, Slovenia (e-mail: vito.starc@mf.uni-lj.si)

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method based on cubic spline line interpolation for removing base line wander (low-frequency drift; effect of respiration) has been incorporated in the present computer software.

A slightly modified version of the R-peak detection algorithm introduced by Manikandan and Soman was implemented [16]. The block diagram of the modified R-peak detection algorithm is shown in Fig. 1. It consists of four stages: digital filtering, Shannon energy envelope extraction, peak-finding logic and true R-peak locator as was contained in the original algorithm [16]. However, one crucial factor i.e. the direction of R-wave in ECG signal was not considered in the original algorithm, but has been incorporated in the present implementation. The previously proposed algorithm is sometimes unable to find the R-peak in ECG signal, especially when the amplitude of R-wave and Q-wave are similar or the amplitude of R-wave is relatively smaller in downward direction.

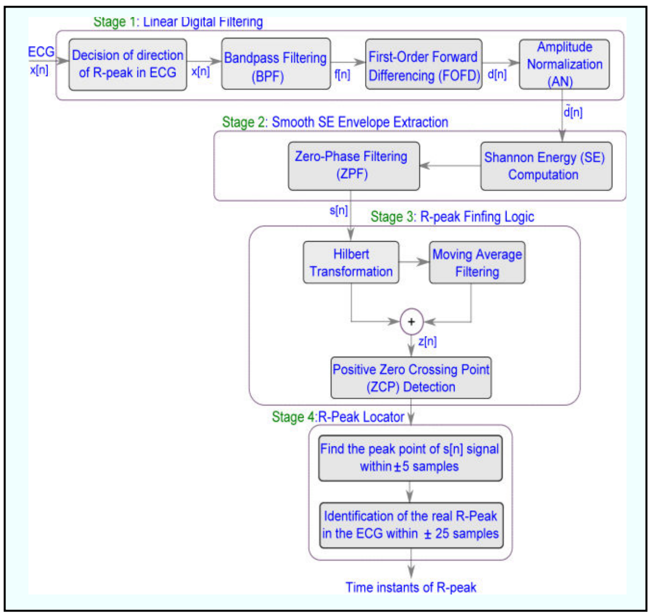

Figure 1. Block diagram of the robust R-peak detection algorithm

To determine the direction of R-wave, initially, a 4[th] order high pass Butterworth IIR filter has been applied on the input ECG (0.5 Hz) to remove initial base line wander from the ECG signal. This pre-processing step signal is not used further except from the initial determination of the direction of the R-wave. After temporarily removing the baseline wander (i.e. now the ECG signal is assumed to be near the iso-electric line), a 2 sec window is constructed. Then, a total of 15 windows are created from the whole input ECG signal. After that, the maximum and minimum amplitude of samples in each window for the whole duration of ECG signal are computed and averaged the maximum and minimum amplitudes separately in their absolute values. If the average absolute minimum amplitude is higher than the average absolute maximum amplitude, then the R-wave is assumed to be negative direction (i.e. downward) and is transformed to positive direction for only processing the signal in the rest of the stages otherwise the R-wave is believed to be positive direction (i.e. upward) in input ECG signal $x[n]$ (see Fig. 1).

Then, the next steps are similar to those described in detail in the article [16] except from a new step that is incorporated in the stage four (R-peak Locator) to find the true R-peak accurately, as shown in Fig. 1. Thus, the R-peak detection algorithm has been implemented.

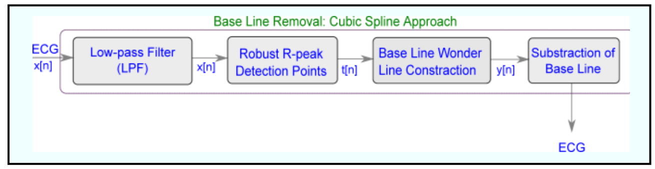

Figure 2. Baseline wander removal steps

The second improvement of the pre-processing stage involves the implementation of the baseline removal algorithm from the ECG signal. It consists of four steps (see Fig. 2). Initially, a low pass Butterworth filter is applied to remove the high frequency from the ECG signal (40 Hz). We have observed that the construction of baseline wander (cubic spline line) is very sensitive to high frequency noise near the Q-wave, because the construction of cubic spline line becomes corrupted. After removing high frequency noise, the R-peak detection algorithm is used to obtain R-peak time instants in the ECG signal. Based on physiological considerations it is assumed that the Q-points are about 50 ms before the R-peak time instants. Therefore, the iso-electric points are considered just before the Q-points in this study. After that, the baseline is constructed by cubic interpolation by using the same sampling frequency as the input ECG signal. Finally, the baseline is subtracted from the ECG signal and this ECG signal is used for the quantification of beat-to-beat QT interval variability.

C. *Statistical Analysis*

The standard deviation of beat-to-beat QT interval was considered as a marker for QTV in simulated ECG. To investigate the performance of different algorithms for quantification of QTV, one-way ANOVA and Newman-Keuls multiple comparison test have been used in this study. The test results were considered statistical significant when $p < 0.05$.

III. RESULTS

The updated approach has been tested on the same simulated ECG as described in the article [23] for the comparison of QTV measurement accuracy with the original method as well as conventional and template time shift methods. The T-wave acquisition range (TWAR) was same between 0.6% to 6.4% as described by Baumert and co-workers [23].

A. *Effect of noise on QTV measurement accuracy*

The updated approach showed lower (one-way ANOVA, $p < 0.005$) noise susceptibility compared (see Fig. 3A) to the conventional and original template stretching method. The Newman-Keuls multiple comparison test showed comparable artificial QTV values ($p > 0.05$) between updated approach and template time shifting method. In addition, both methods produced artificial QTV less than 2 ms when the TWAR was greater than 1.3%. Finally, the updated approach did not reject any beat even at the lowest TWAR, where the original template stretching method rejected two percent of beats [23].

B. *Effect of baseline wander on QTV measurement accuracy*

The updated method showed a significant improvement for quantifying QTV compared to the original method ($p < 0.0001$) and provides the least artificial QTV (see Fig. 3B) compared to conventional method, but was comparable with the template time shift method ($p > 0.05$) based on Newman-Keuls multiple comparison test. On average, artificial QTV was 0.67 ms in the updated approach, where with template time shift method artificial QTV was 1.48 ms. Finally, the updated approach showed a significant improvement ($p < 0.05$) in terms of beat rejection (i.e. no beat was rejected) compared with the original template stretching method [23]. In original template stretching method rejects 88%, 74%, 60%, 43% and 10% of beats from lowest to intermediate TWAR values [23].

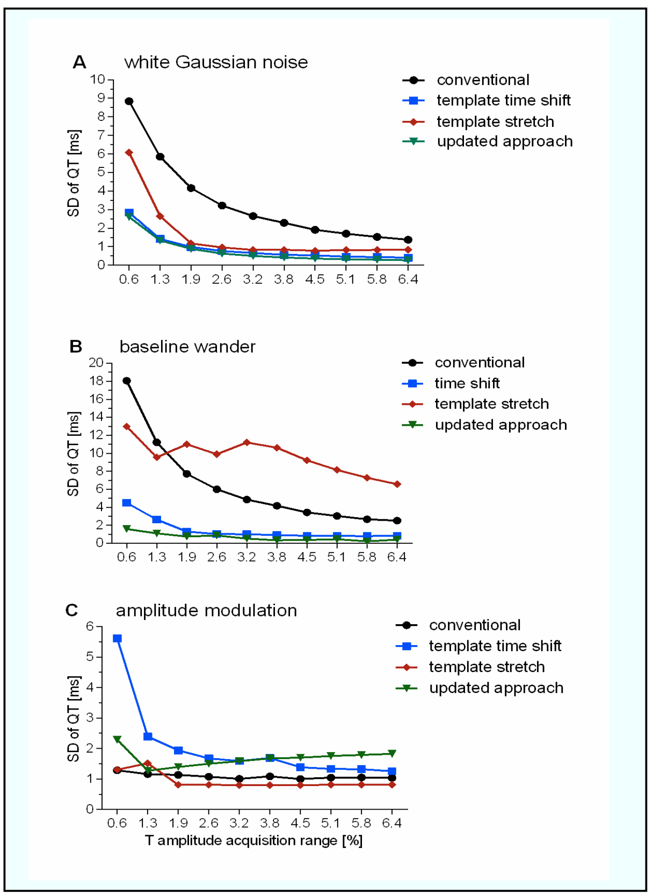

Figure 3. Performance of QTV measurements

C. *Effect of amplitude modulation on QTV measurement accuracy*

Mean artificial QTV was less than 2 ms (1.68 ± 0.28 ms) with the updated approach (see Fig. 3C) where in the previous approach it was less than 1 ms (0.93 ± 0.26 ms). On the other hand, the template time shift method had the highest artificial QTV (2.02 ± 1.31 ms). The automated beat rejection was only 15% from each of the simulated signals, whereas it was 36% when using the original template stretching algorithm [23].

IV. Discussion

Reliability of the improve template stretch algorithm

Effect of noise on QTV measurement

It has been suggested in [23] that the original template stretching technique is more susceptible to white Gaussian noise than the template time shift method, but less susceptible than the conventional technique. However, with the updated pre-processing the template stretch approach showed a different scenario under the same experimental setup. The updated approach demonstrated lower noise sensitivity compared to the conventional method and original template stretching method. The updated approach and template time shifting method provide similar QTV values based on Newman-Keuls multiple comparison test. These two methods produced overall average errors less than 1 ms and error less than 0.7 ms while the TWAR was greater than 1.3%. Further, it was found that there was no beat rejected by the updated approach even in the lowest TWAR, which is in line with conventional, and template time shifting techniques.

Effect of baseline wander on QTV measurement

A previous study showed that the template stretching technique performed worst in the presence of baseline wander and the best performance was achieved by the template time shift approach [23]. However, the updated approach showed significant improvements with compared to the original template stretch method and conventional method. The reason for higher QTV by original template stretch method can be partially explained by this study. Firstly, may be the filter was not capable for removing baseline noise completely in the original method [13]. Secondly, as a result, the automated R-peak detection employed [12] in the original template stretch method was limited for finding the accurate R-peak in the ECG. In contrast, the updated approach demonstrated lower artificial QTV values (less than 2ms), which were comparable with those of the template time shift method. Moreover, the updated template stretching approach provided a significant improvement in terms of beat rejection (i.e. no beat was discarded) compared with the original template stretch method.

Effect of amplitude modulation on QTV measurement

A recent study suggested that the template stretch method had less QTV compared to conventional and template time shift method [23]. However, the underlying mechanism of obtaining lower QTV by original template stretch method was not completely understood [23]. The updated approach showed a significant improvement even in amplitude modulated conditions. In addition, the present approach may explain the reason for lower QTV in the original template stretch technique where 36% of beats were discarded from each simulated signal. Our result showed that the original template stretch method rejects more beats. This disparity in performance might be partly explained as the previous method highly depends on the threshold based R-peak detection [12] where it fails to detect the lower amplitude of QRS. As a result, only higher amplitude of QRS-T waves were considered for computing the QT interval in the signal and thereby it showed lower artificial QTV compared with all other techniques. Furthermore, in the original template stretch method [13], it was assumed to be PVC beats (36% beats from each simulated signal) if the algorithm fails to detect the lower amplitude of QRS-T wave due to the amplitude modulation. Average artificial QTV was found less than 2 ms with updated approach where the automated beat rejection was only 15% from each of the simulated signal. In practice, real ECG signals might not be exactly the same as the simulated signals with amplitude modulation and thus the updated approach appears to be more robust.

V. Conclusion

In conclusion, the test results suggest that the updated ECG pre-processing approach outperforms the existing algorithm when evaluated on the simulated ECGs for analysing beat-to-beat QTV. Further, the updated approach seems to perform comparably to the template time shift method.

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