Modified ∏-shaped Finite Impulse Response Filter for Stabilization of QT measurement

Jing Wu[1], Xiaojuan Xia[2], Jean-Philippe Couderc[1,2]

[1]Department of Electrical and Computer Engineering, [2]Center for Quantitative Electrocardiography and Cardiac Safety, University of Rochester, Rochester, NY, USA

Abstract

In drug-safety study, the measurements of QT intervals require to have a level of precision to detect small drug-induced prolongation (~ 5 msec). This paper discusses a modified approach of ∏-shaped FIR Filter to optimize the quality of signal and improve the stability of QT/QTc interval measurements.The proposed filter is designed to have a time-dependent frequency characteristic based on pre-defined fiducial points of the EKG. The radius of regular ∏ -shaped FIR filter is modified to obtain different frequency characteristics between QRS and the repolarization interval. The evaluation of QTc stability was based on the standard deviations of QTc interval when measured from Holter ECG signals from 20 healthy subjects filtered with the proposed five versions of the∏ -shaped FIR filter. The result shows that the standard deviation of QTc interval with hybrid filter revealed an averaged 50% increase of stability in comparison to other filter, such as the regular ∏-shaped FIR filter, and the traditional FIR filters.

1. Introduction

The electrocardiogram (EKG) is a widely used clinical tool in the assessment of drug cardiotoxicity linked to cardiac ventricular repolarization. QT/QTc prolongation is used as a surrogate marker of the risk for torsades de pointes, and a dangerous polymorphic ventricular arrhythmias associated with a prolongation of the QT/QTc interval. The level of precision of the QT measurement is very high and the use of automatic or highly-automatic measurements is slowly adopted validation effort such as the work published Handzel et al. [1]. Among the factors that can affect the precision of the QT interval measurements, the presence of noise components coming from power line interference, body movement (electromyograms), quality of skin-electrode interface and other environment electrical sources have to be considered. These external factors can pollute the EKG signal and make interpretation and measurements of QT interval more challenging (requiring human interaction). The recording frequency content of the ECG signal in clinical settings is recommended to be between 0.05 Hz and 150 Hz by the American National Standard Diagnostic Electrocardiographic devices [2]. This frequency band does cover all bandwidth requirements for the ECG interpretation by merging the frequency fingerprints of all recorded complexes and waves of the ECG surfaces. However, it has been described that these waves have different frequency profiles. Therefore, a way to improve noise-removal technique is to design a filter with frequency characteristics depending on a-priori information of the ECG.

This paper aims to optimize the quality of filtered signal based on a filter with different frequency across time and discusses a modified approach of ∏-shaped FIR Filter to optimize the quality of signal and improve the stability of QT/QTc interval measurements. The proposed filter is designed to have a time-dependent frequency characteristic based on pre-defined fiducial points of the EKG. The radius of regular ∏-shaped FIR filter is modified to obtain different frequency characteristics within QRS and the repolarization interval. This hybrid filter is compared to its simple forms (including 5 radiuses N=3, 5, 8, 10, 15). We compared the standard deviation of QT/QTc interval between the hybrid filter and the single-radius filters (radius N=5, 10, 15, 20).

2. Methods

2.1. ECG signals

The ECG dataset used for this paper is from “Thorough QT Study # 2” of the Telemetric and Holter ECG Warehouse [3]. This study is a single-center, single-dose, randomized, placebo-controlled study. Twenty subjects are chosen randomly from the baseline for the study. The data signals are Holter ECGs with a sample frequency of 1000 Hz. We selected lead I signals from the total 12-lead ECG and the randomly ECG epochs of five minutes during daily activities from the 24-hour ECGs. All files are from 20 subjects including 6 females (45±9 yrs) and 14 males (40±10 yrs). The duration of the ECG signal was 5 minutes and included in average 30,000±20 beats.

2.2. Signal-to-noise ratio (SNR) estimation

The SNR is defined as the ratio of the mean signal value (μ) to the standard deviation of the signal values (σ), that is, SNR = 20log (μ / σ). We selected the SNR to evaluate the performance of the candidate filters. We define the SNR improvement to be the value of the system output SNR (in dB) minus the input SNR (in dB). The primary input to the system varies from relatively noise-free (input SNR: 20 dB) to very noisy (input SNR: 5 dB) with 2.5 dB increment. Following this strategy, we measured seven different levels of noises. Then, we compared the SNR values of each candidate filter based on the same signals.

2.3. ∏-shaped finite impulse response (FIR) filter

This ∏-F filter is a filter, with a given radius for averaging around the center points. The filter was implemented by Slonim et al. [4], which is only one addition, one subtraction and a single division for each sample.

$$y(i) = 1/N \cdot [1/2 \cdot (x(i-N) + x(i+N)) + 1/2 \cdot (x(i-(N-1)) + x(i+(N-1))) + \cdots 1/2 \cdot (x(i-1) + x(i+1))]; \qquad (1)$$

where N is the maximum radius for one specific point, x and y are the input and output signal, respectively. The bandwidth of the ∏-F filter is dependent on the number of points defining the window. The proposed filter has dynamic frequency range. The low-pass frequencies are 110Hz, 72Hz, 47Hz, 39Hz, and 26Hz for filter with radius 3, 5, 8, 10, and 15, respectively.

2.4. QRS detection

To apply the filters described in Section 2.3, we need the fiducial points (Q and J points) defining the ECG sections associated with each filter designs. So, we detected the R peak to apply the specific filter into each part (P wave, T wave, QRS complex) for each cardiac beat. We use the QRS detection algorithm developed by Pan and Tompkins (1985). The method includes four steps: 1) band-pass filter 2) the differentiator 3) squaring and 4) time averaging [5].

This method was developed using MATLAB (Natick, MA). The QRS detection algorithm was validated using the annotation from the THEW database. The corresponding assessment was done quantitatively from the 20 subjects and described in the section 3.1. The RR interval was measured and then compared to the one from the annotation file available in the THEW database (these were manually adjusted). We defined a difference less than 10 ms between RR intervals to be acceptable, RR differences larger or equal to 10 msec were labeled wrong. We reported an accuracy rate in percent computed as the ratio between the number of right detection to the number of beats.

2.5. QT/QTc measurements

The QT interval represents the recovery time of the heart ventricles, which is a measure of duration (in msec) between the start of the Q wave and the end of the T wave. The Q point is identified as the onset of the QRS complex. The end of the T-wave is determined by finding t_c first, which is the time at which the second half of T wave has the maximum slope. The searching of t_c starts at the apex of T-wave (ta) and ends at t_f or half the length of the T wave when detection of t_f failed. The t_f is the point at which the sign of the linear regression slope changes. This is a modified version of the tangent method described by Lepeschkin and Surawicz [1,6]. The heart rate correction is based on the Fridericia's formula [7]: $QTc = \frac{QT}{(RR)^{1/3}}$. We assessed the stability of the QT/QTc interval by comparing the standard deviations of beat-to-beat QTc interval durations across normal sinus beats within the 5 minute-ECG epochs. The standard deviation was measured for the five ∏-shaped FIR filters (described in section 2.3).

3. Results

3.1. SNR evaluation and QRS detection evaluation

For the SNR evaluation, it was observed that the SNR curve in comparison to the regular averaging filter does not increase much, especially in the case of N=3 and N=5 filters, which shows in the following figure that these two curves are almost horizontal. The reason for this could be that the noise-reduction of the system with the regular averaging filter does not change much with the nature of the primary input. Since each regular ∏-F filter with radius N=3, 5, 8, 10, 15 does not have a significantly increase in the SNR improvement (show in the figure), then we consider to try the combination of them to achieve the better performance. Since filter with N=3 performs better noise-removing result in the QRS complex section without any amplitude attenuation, and one with radius N=15 achieves better filtering performance in the P & T waves, then an comprised filter is obtained by this combination of regular ∏-F filters. In the case of SNR evaluation represented in figure 1 and in comparison to the regular ∏-F filter, the system's SNR increases from 21 to 45 dB significantly as the input signal becomes more and more heavily contaminated by the noise. The figure reveals that this hybrid filter provides better reduction of noise effect.

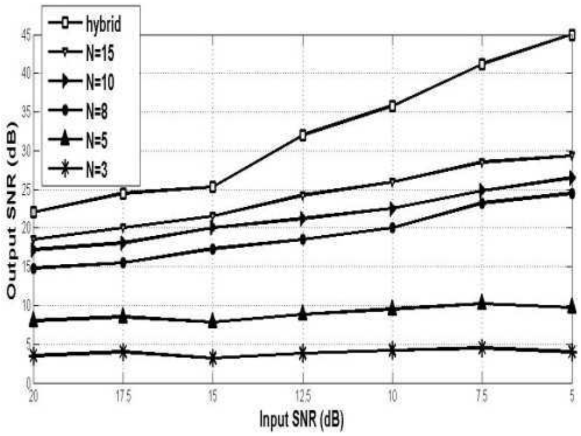

Figure 1. Description of SNR values after filtering for 7 different SNR inputs. The figure reveals the compared performance of the hybrid filter.

Using the method mentioned in the section 2.3, the accurate rate for R peak detection was 99.1±0.5 %, therefore validating the reliability of our R peak detection algorithm.

3.2. QT/QTc evaluation

The variability of QTc duration of filtered signal with regular filter N=5, 10, 15, 20 was calculated by averaging the standard deviation of QTc which was 10, 13, 10, 10 msec, respectively. These results corresponded to 42%, 76%, 37% and 45% decrease stability in reference to the hybrid filter. Table 1 summarizes results.

Table 1. Standard deviation of QT and QTc (average value).

	Hybrid	N=5	N=10	N=15	N=20
QT	5.7±2.1	7.3±3.3	9.2±5.0	6.3±2.3	6.4±2.2
QTc	7.3±2.2	10.2±3.2	12.6±4.8	9.8±2.7	10.4±3.0

Since the standard deviation reported in table 1 is its average standard deviation across out study population, the lower values show more stability of QT/QTc measurement. The hybrid filter achieves the best stability of QT/QTc interval.

3.3. QT variability and T wave amplitude

We investigated the influence of T wave amplitude on the stability of QTc measurement. By plotting the relation between the standard deviation of QTc and T wave amplitude, which is represented in the figure 2, variability of QTc measurement was greater for low amplitude T wave, and especially for those T waves with the amplitude inferior to 0.25mV. The linear regression is provided in figure 2. The slope of regression line is -1.0. Also, 88% of the total variation of standard deviation of QT interval (QT_std) is explained by the variation in T wave amplitude. The P value is $1.0*e^{-9}$, representing a highly significant correlation. The QT interval stability was 3 times higher where T wave amplitude was inferior to 0.25mV.

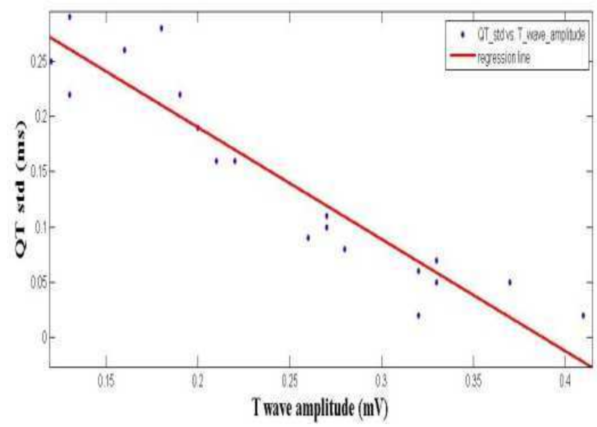

Figure 2. Standard deviation of QT interval versus T wave amplitude. The figure reveals strong dependency of the stability to the amplitude of T wave.

4. Discussion

We propose the use of a modified version of the ∏-shaped FIR filter to minimize the stability of the measurements of the QT interval from the surface ECG recordings. The strategy we propose rely on prior knowledge of the location of the QRS onset and J point for each cardiac beat of the ECG. Then, we use these fiducial points to apply different filter configurations. This strategy is not optimal in terms of computing resources and computing time, yet it permits to increase the stability of the QT interval measurement in comparison with simple ∏-shaped FIR filter configuration as described in reference [4]. Our work included the development of a QRS detector (accuracy = 99.1±0.5 %), evaluation of the hybrid filter performance in terms of SNR, and an assessment of the QT/QTc measurement stability (in comparison to five regular averaging filters). Our results show that the hybrid filter was associated with a larger reduction of noise effect and more stability in measuring the QT/QTc interval.

Filter effects on QT measurement has been studied in the past by several groups. McLaughlin [8] focused on the influence of T wave amplitude on the accuracy of QT measurement. Similarly to our approach, this group implemented a filter to reduce myopotential and electrical noises. In their study, a 2^{nd} order low_pass Butterworth recursive filter was used. By plotting the relation between the standard deviation of QT and T wave amplitude, they demonstrated that variability of QT measurement was greater for low amplitude T wave, and especially so for those T wave with an amplitude inferior to 0.25mV. Then, they concluded that the amplitude of T wave is one of the primary factors influencing the accuracy of QT measurement. In their study, QT interval variability was 1.8 to 2.7 times higher in ECGs where the T wave amplitude was inferior to 0.25mV, which compare to 3 times in our study based on the result from section 3.3. Based on this evaluation, we confirm that the stability of QT measurement is significantly lower when T wave amplitude is below 0.25mV. Our work highlights that T wave amplitude remains an important factor for QT interval measurement stability. The effect of T wave amplitude on QT stability should be considered systematically in relation to T wave amplitude when using a slope-based technique. Precisely, this method is dependent on the overall morphology of the T wave including the amplitude. Consequently, the use of another technique may be required to reduce the effect of T wave amplitude on QT measurement. One method such as the one based on the amplitude threshold may perform better.

Another method by Chen [9] for QT measurement used Kalman filter (KF) to achieve smoothed ECG signals. The difference between this method and ours is that Chen et al. did not investigate the effect of T wave amplitude on QT stability and thus such method cannot be compared to previous reports. Future work will challenge the hypothesis that Kalman filter is less dependent on T wave amplitude for QT measurement stability.

5. Conclusion

We investigated the hybrid filter to increase stability of QT measurement. The result shows that the standard deviation of QTc interval with hybrid filter was associated with 50% increased stability yet our method still depends on T wave amplitude with a loss of stability for low T wave amplitude.

Acknowledgements

Data used for this research was provided by the Telemetric and Holter ECG Warehouse of the University of Rochester (THEW), NY.

References

[1] R Handzel, C Garnett, M Li, S McNitt, S Polonski, X Xia, JP Couderc, "Comparison of Highly-Automatic versus FDA-Submitted QT Measurements for the Detection of Moxifloxacin Induced Prolongation of the QTc Interval". Computers in Cardiology 2008; 35:693−696.

[2] Paul Kligfield, Leonard S. Gettes, James J. Bailey, "Recommendations for the Standardization and Interpretation of the Electrocardiogram: Part I: The Electrocardiogram and Its Technology: A Scientific Statement From the American Heart Association Electrocardiography and Arrhythmias Committee, Council on Clinical Cardiology; the American College of Cardiology Foundation; and the Heart Rhythm Society Endorsed by the International Society for Computerized Electrocardiology". JACC Vol. 49, No. 10, 2007.

[3] Courderc JP. "The Telemetric and Holter ECG Warehouse Initiative (THEW): a Data Repository for the Design, Implementation and Validation of ECG-related Technologies". In Conf. Proc. IEEE Eng Med Biol. Soc. 2010; 6252-6255.

[4] T-YM Slonim, MA Slonim, EA Ovsyscher, "The use of simple FIR Filters for filtering of ECG Signals and a New Method for Post-Filter Signal Reconstruction". Computers in Cardiology 1993, Proceedings. Publication Year: 1993 , Page(s): 871 – 873.

[5] Valtino X. Afonso. " ECG QRS detection". "Biomedical Digital Signal Processing" Page(s): 236-264.

[6] Zhong W, Moody GB, Jiang D. A Robust "Open-source Algorithm to Detect Onset and Duration of QRS Complexes".Computers in Cardiology 2003;30:737- 740.

[7] Bazett HC. (1920).b "An analysis of the time-relations of electrocardiograms". Heart (7):353–370.

[8] N B MuLaughlin, R W F Campbell, A Murray, "Accuracy of four aotumatic QT measurement techniques in cardiac patients and healthy subjects". Heart 1996; 76:422-426

[9] X Chen, W Xie, L Dong, ZK Tin, M Sankaranarayanan "Reliable Automated QT Interval Measurement for Clinical Evaluation". Computers in Cardiology 2006; 33:373−376.

Address for correspondence:

Jing Wu
Conant Rd,
Rochester, 14623, NY, USA
Jingwu@ece.rochester.edu