Retraction

Retraction: Development and Validation of QT Interval Measurement Algorithm Using Lab windows/CVI (J. Phys.: Conf. Ser. 1916 012004)

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IOP Publishing regrets that our usual quality checks did not identify these issues before publication, and have since put additional measures in place to try to prevent these issues from reoccurring. IOP Publishing wishes to credit anonymous whistleblowers and the Problematic Paper Screener [1] for bringing some of the above issues to our attention, prompting us to investigate further.

[1] Cabanac G, Labbé C and Magazinov A 2021 arXiv:2107.06751v1

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Development and Validation of QT Interval Measurement Algorithm Using Lab windows /CVI

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Abstract. During the last few years, a lot of study and research on the analysis of Electrocardiogram(ECG) has provided an intensive approach for the diagnosis of various heart diseases which is a leading cause of death worldwide. By examining the ECG waveform it is possible to obtain a number of useful measurements. The most important of these is the "QT interval" measurement because an abnormal QT interval can be allied with ventricular arrhythmias and sudden cardiac death. The QT interval is obtained by the detection of onset of the QRS complex and offset of the T wave. This work includes an endeavor for the efficient measurement of QT interval which mainly comprises of five stages like finding R peak using Pan Tompkins algorithm, detection of QRS onset, detection of T wave offset, measurement of QT interval and QT interval correction. The measurement of QT interval is implemented using LabWindows/CVI (C for Virtual Instrumentation). The performance evaluation of R peak detection is tested as per AAMI/ANSI/IEC 60601-2-47 standards using the databases that are available in Physionet like QT Database and MIT-BIH Arrhythmia Database. The performance evaluation of QT interval measurement is tested using a MindrayuMEC 10 Multiparametric monitoring unit and the algorithm achieved an accuracy of 96.73% for QT interval measurement.

Keywords: ECG, QT interval, Pan Tompkins algorithm, QT interval correction, Labwindows/CVI, Physionet.

1. Introduction
Normal ECG wave comprises of P, Q, R, S, T waves, QRS complex, PR, QT, RR, ST intervals and ST segment. The evaluation of ECG should also comprise an effort to interpret the QT interval in order to assess the risk of sudden cardiac death and arrhythmias which are related to the QT interval. QT interval is the time interval from start of the depolarization of ventricles, which is denoted by the QRS complex within the ECG and the completion of the repolarization which is represented by the T wave in an ECG waveform. The QT interval is measured from the start of the QRS complex till the end of the T wave in an ECG. Normal
duration of QT interval is 0.36 to 0.44 seconds for the heart rate (HR) of 60 beats per minute (bpm). Abnormally long QT interval or abnormally short QT interval is related to greater risk of developing abnormal heart rhythms and sudden death. QT interval prolongation can result from an increased action potential duration of the ventricular myocardium. Few people can be born with the prolonged QT interval, while others can have prolonged QT interval which is induced by the influence of medicines that will affect cardiac repolarization.

The short QT interval is a congenital syndrome which is caused by genetic faults. It can impose a high risk of ventricular flutter and ventricular fibrillation, particularly in children, infants and juveniles, which is mainly caused by an imbalance in potassium currents. The accuracy of QT interval measurement in ECG has become very important due to the need of recognizing the probable pro-arrhythmia adverse effects of novel drugs during clinical trials based on ECG. The chief reason behind the complications are due to intricate behaviour of cardiac repolarization and ambiguous nature of the end of repolarization in ECG. QT interval is said to be inversely connected with the heart rate because the QT interval accelerates at the slower heart rates and decelerates at the higher heart rates [1]. So, in order to decide whether the QT interval lies within normal limits and to improve the determination of ventricular arrhythmias, the QT interval has to be adjusted for the HR. The QT interval that is adjusted according to the heart rate is called as the corrected QT interval (QTc interval). The algorithm developed in this work provides a proficient way of QT interval measurement by using LabWindows/CVI 2012 SP1 ANSI C programming environment.

2. Literature Review

[2] explained about a real time QRS detection algorithm. The algorithm that is developed in this work does digital analysis of width, slope and amplitude in order to efficiently recognize the QRS complexes. A digital band pass filter is used for pre-processing of ECG which in turn reduces false detections that can be caused by the different types of intrusions present in ECG signals.

[3] developed an algorithm for feature extraction in ECG signals using a method called adaptive thresholding for extraction of various features, detection of different peaks. It was achieved by extracting ECG features such as P and T wave, PR, QT, RR, ST intervals QRS complex, and ST segment.

[4] explained about the ECG feature extraction in temporal domain and also recognition of different heart disorders. It was achieved by extracting ECG features such as P and T wave, PR, QT, RR, ST intervals QRS complex, ST segment and deviations of the ST segment.

[5] discussed about detection of QT interval in ECG using trapezium area method and Pan Tompkins algorithm. This work comprises an effort for calculating QT interval in ECG using an automatic computerized algorithm. The methodology used in this algorithm was to find more consistent QT interval measurement by using the combination of Pan Tompkins and Trapeziums Area method for T wave end detection.

[6] focused on the development and validation of an automatic QT interval detection algorithm. This work aimed to develop an algorithm using tangent method for QT interval detection which can even be applied on a beat to beat basis irrespective of the T-wave morphology and is also robust to orientation of the heart axis.
focused on improving the preprocessing of ECG for QT interval variability measurement on beat to beat basis. In this work an effective baseline removal algorithm was employed by replacing the R peak detection algorithm in existing computer software. The ECG data was simulated with static QT intervals containing baseline wander and Gaussian noise to test the performance.

[8] designed a novel fully automatic method which is based on continuous wavelet transform to determine QT interval. Onset of the Q wave and offset the T wave was obtained in this work.

[9] explained about analysis of the ECG signal in order to detect the ischemic episodes and also the heart rate. This work followed five steps for the efficient detection of ischemic episodes and heart rate such as preprocessing, extraction of different ECG features, detection of heart rate, classification of beats and recognition of ischemic episode.

3. Software

The software used for the implementation of QT interval measurement is LabWindows/CVI 2012 SP1. LabWindows/CVI (C for Virtual instrumentation) is an ANSI (American National Standards Institute) C programming environment, it can be used to link, compile and debug ANSI C programs in the LabWindows/CVI environment.

4. Database

QT Database: 50 records are considered for R peak performance evaluation and 20 records are considered for QT interval performance evaluation. The recordings are digitized at 360 samples/sec.

MIT BIH Arrhythmia Database: 20 records are utilized for the R peak detection performance evaluation. The recordings are digitized at 360 samples/sec.

5. Methodology

The ECG records from the body surface and accounts the differences in electrical potential generated by the heart. This ECG has to be processed in order to extract vital information for the diagnosis of various cardiac diseases. Therefore, this work presents a method that processes the ECG and extracts different features for the purpose of R peak detection, Q wave detection, T wave detection, measurement of QT interval, calculation of QTc interval as shown in Figure 1.
5.1 Pre-Processing

The pre-processing of raw ECG signal is required in order to remove various types of noise such as power-line interference, T wave interference, muscle noise and baseline wander etc. Among these types of noise, power-line interference is most significant and it can strongly affect the ECG signal analysis. Therefore, raw ECG signal is initially preprocessed by using Finite Impulse Response (FIR) band stop filter with a cut off frequency of 40-60Hz to remove the power-line interference.

5.2 R Peak Detection

The “Pan Tompkins” algorithm for QRS detection is used for R peak detection. The QRS complexes are detected based on the investigation of slope, amplitude, and width of the ECG wave digitally. The preprocessed signal is made to pass through different phases such as differentiator, squaring, and moving window integration before the thresholds are fixed and QRS complexes are identified.

5.2.1 Differentiation

After preprocessing of ECG signal the following step is differentiation, which is used for finding the high slopes that will discriminate the QRS complexes from other waves of ECG such as P and T wave. The differentiation process suppresses P and T waves which are the lower frequency components, and provides a larger gain to the QRS complex which is a high frequency component in ECG.

5.2.2 Squaring

After differentiation, point by point squaring is done on the signal. The squaring process makes all data points of the ECG signal positive and also does amplification of the output arising from the differentiation step by highlighting the higher frequencies. Squaring operation emphasizes the higher differences which is obtained from QRS wave and suppresses the smaller differences which are obtained from P and T waves.
5.2.3 Moving window integration
Moving window integrator adds up the area that comes under the squared waveform above a particular interval which is called as the window width, the integrator then progresses one sample interval ahead, and then integrates the newly defined interval window. The window chosen is 30 samples wide.

5.2.4 Adaptive thresholding
To detect the QRS complexes two different threshold levels are used. One level is used to threshold the filtered ECG signal, and the other level is used to threshold the signal obtained after the moving window integrator. One threshold level is half the other. Initially the higher of the two thresholds is applied, the lower threshold is used when none of the QRS complexes are found in a particular interval of time and search back technique is essential. For a QRS complex to be recognized, a peak must be identified as a complex in both the moving window integrated and also filtered waveform. Once a valid QRS complex is recognized, there is a 200ms refractory period before the next QRS complex can be spotted because QRS complexes cannot possibly occur closely than this according to physiology. When a QRS complex is detected after the end of the above mentioned refractory period but less than 360ms of the previously detected QRS complex a decision has to be made in order to determine whether the current detected QRS complex is properly recognized or whether it is a T wave. If the maximum slope which occurs during this waveform is less than half of the previously detected QRS complex, it is declared as a T wave or else it is declared as a QRS complex.

5.3 Calculation of RR interval and HR
RR interval is calculated by taking the difference between the present and the previous R peak location as shown in equation (1),

$$RR = R_{peak(i)} - R_{peak(i-1)}$$  \( (1) \)

Where RR is the calculated RR interval, R_{peak(i)} is the present R peak location and R_{peak(i-1)} is the previous R peak location.

The calculated RR interval is multiplied by the time required for plotting one sample i.e. for the sampling rate of 250 samples/sec, the time required for one sample is 4ms. HR is calculated by multiplying 60 to the inversed RR interval and the resulting HR is expressed in beats/min as shown in equation (2),

$$HR = (1/RR) \times 60$$  \( (2) \)

Where HR is the heart rate and RR is the RR interval.

5.4 Q Wave Detection
The Q wave peak is detected with the help of valid R peak location. Q peaks are detected by finding a minimum value within the Q period, which is 55ms before the R peak location. From the detected Q peak location, onset of the QRS complex is detected by establishing a search window of 20ms before the Q peak. A maximum value in the search window is the QRS onset point. Similarly, S peaks are detected by finding a minimum value on S period, which is 55ms after the R peak location. From the detected S peak location, offset of the QRS complex is detected by forming a search window of 20ms after the S peak. A maximum value within the search window is the required QRS offset point.

5.5 T Wave Detection
T peaks are detected with the help of valid R peak location. T wave is detected by establishing a search window based on the i-th detected R peak location and i-th RR interval which is an adaptive technique for finding the T wave peak and T offset. Within each detected RR interval, t1 and t2 are chosen i.e., two discrete time instants, in order to confine the T wave end search. The two time instants will vary for two different current RR interval i.e. if the RR interval is less than 0.88sec and for the RR interval greater than or equal to 0.88sec shown in equations (3)-(6).

If RR interval is less than 0.88sec,

\[ t_1 = ((0.15 \times RR(i)) + R(i) + 0.148) \]  
\[ t_2 = ((0.7 \times RR(i)) + R(i) - 0.036) \]

If RR interval is greater than or equal to 0.88sec,

\[ t_1 = (R(i) + 0.28) \]  
\[ t_2 = ((0.2 \times RR(i)) + R(i) - 0.404) \]

Where \( R(i) \) is the i-th amplitude of the filtered waveforms R peak location, RR(i) is the i-th RR interval calculated by taking the difference between R(i) and R(i-1).

![Figure 2. Search window for T wave detection](image)

T peak is detected within the search window created by the two time instants t1 and t2[10]. In the created search window, T peak is detected as the absolute maximum positive or negative value. After the detection of T peak, T offset is detected within a search window created by T peak location and t2 time instant. If the detected T peak is positive, then T offset is detected as the minimum value point within the search window. Similarly, if the detected T peak is negative, then T offset is detected as the maximum value point within the search window as shown in Figure 2. To verify that the T wave boundaries are not overlapping with the S wave offset, QRS offset is used.

5.6 Calculation of QT Interval

After the detection of valid R peaks, Q wave onset point and T wave offset point, the next step is to calculate the QT interval. QT interval of each and every beat in an ECG record is calculated by using the following equation (7),

\[ QT\text{ Interval}(i) = T\text{ offset}(i) - QRS\text{ onset}(i) \]  

Where QT Interval(i), T offset(i) and QRS onset(i) are QT interval value, T wave end position and Q wave onset position of the i-th beat, respectively.

The calculated QT interval is multiplied by the time required for plotting one sample. Finally, the QT interval is averaged over 10sec window to avoid the small variations of QT interval which leads to greater changes in the calculation of the corrected QT interval. The unit of calculated QT interval is seconds.

5.7 QT Interval Correction

The QT interval is inversely related with the heart rate. Faster heart rate shortens the QT interval and slower heart rate prolongs the QT interval. The QT interval should be corrected for preceding RR interval and HR using different QT interval correction formulas and the corresponding interval is called as corrected QT interval (QTc). The formulas to correct the QT interval are as shown in Table 1.

| Method      | Correction Formulae                   |
|-------------|---------------------------------------|
| Bazett      | QTc=QT/RR^{1/2}                       |
| Fridericia  | QTc=QT/RR^{1/3}                       |
| Framingham  | QTc=QT+0.154*(1-RR)                  |
| Hodges      | QTc=QT+0.00175*(HR-60)                |

Where QTc is the corrected QT interval, QT is the calculated QT interval which is averaged over 10 sec window, RR is the RR interval and HR is the heart rate which is averaged over 10 sec window.

5.8 Delta QTc (ΔQTc or dQTc)

According to literature survey, approximately 40% of the patients with long QT syndrome can have a nondiagnostic QTc interval at rest. Therefore, treadmill and cycle exercise stress testing are done in order to monitor the variations in QTc values. Based on the literature survey Framingham correction formulae showed the best rate correction and the remaining formulas overestimated the number of patients with potentially dangerous QTc prolongation, which can lead to unnecessary safety measurements. Therefore, in the present work, QTc value which is obtained by applying Framingham correction formulae is used for delta QTc calculation. Delta QTc is calculated by subtracting the previous QTc value from the present QTc value as shown in equation (8),

\[ \Delta QTc = QTc(i) - QTc(i-1) \]  (8)

Where ΔQTc is the change in QTc interval, QTc(i) is the present QTc interval and QTc(i-1) is the previous QTc interval.
6. Results And Discussion

Raw ECG signal is filtered by using FIR band stop filter. R peaks are detected by using Pan Tompkins algorithm. Onset of the Q wave and offset of the T wave are identified based on R peak location. QT interval is calculated using Q onset and T offset. QT interval is corrected by using RR interval, HR and different correction formulas. Finally, delta QTc is calculated.

6.1 Pan Tompkins Algorithm

First strip chart in the uir (user interface resource) displays the original ECG signal, second strip chart shows the filtered ECG signal, third strip chart shows the differentiated ECG signal, fourth strip chart shows the squared ECG signal and the fifth strip chart shows the moving window integrated signal as shown in Figure 3. The uir also includes a ring control which is named as Data, it is loaded with 50 QT database and 20 MIT database. A number is given to each database and the database that has to be processed can be chosen by selecting a particular number. The start, stop, resume and quit buttons are command buttons that work with respect to timer and they can be used to start, stop, resume and quit the processing of signal at any point of time.

![Figure 3. Pan Tompkins algorithm](image)

6.2 QRS Complex Detection

The text box control displays the QRS complex detected text line as shown in Figure 4, two threshold levels of filtered and moving window integrated waveforms and QRS complex sample number whenever a valid R peak is detected is also displayed. The uir also includes numeric box controls which shows the amplitude values of original ECG signal, filtered signal, moving window integrated signal, the numeric box displays the number of QRS complexes detected till then and also QRS numeric box sets to flag 1 whenever a valid R peak is detected and sets to flag 0 all other times. The uir includes an LED that glows to red color whenever a QRS complex is detected and shows black color all other time.
6.3 R Peak Validation

The R peak detection performance is evaluated with the help of R peak information which is present in each record of the database. The ui includes a ring control named original HR, it is loaded with the original R peaks from the database. When the data and the corresponding original HR are selected, the original RR interval and the original HR will be calculated and it is averaged over 10sec window. This original HR average is compared with the 10sec averaged HR which is calculated based on the R peak location that is detected by using Pan Tompkins algori thm. The HR is averaged over 10sec window in order to check the mismatch between original HR and the calculated HR.

The text box displays the mismatch time and the mismatch sample number when there is a mismatch between original HR and the calculated HR. The Figure5 shows a condition where there was no mismatch found between the original HR and the calculated HR for the QT database – Sel16483. The Figure 6 shows the condition where there was a mismatch between the original HR and the calculated HR for the QT database – Sel853. The percentage of Accuracy is computed to measure the performance of the algorithm. For the calculation of accuracy, overall average of both the 10sec averaged HR values are computed and compared.
Figure 6. Case of mismatch for QT database – Sel853

6.4 Q Wave Detection
Q wave is detected using the valid R peak location. The Figure 7 includes numeric box control which displays the QRS complex onset and offset point.

Figure 7. Detected Q onset point and offset point

6.5 T Wave Detection
T wave is detected from valid R peak location. The Figure 8 includes numeric boxes which displays the detected T peak location, T offset location and the number of T waves detected till then.
6.6 Calculation of QT, QTc and Delta QTc Intervals

The UIr includes numeric box control that shows the 10sec averaged QT interval which is expressed in seconds, QTc values obtained by using different correction formulae which is expressed in seconds and also Delta QTc value as shown in Figure 9.

6.7 QT, QTc and Delta QTc Interval Validation
The validation of QT, QTc and Delta QTc intervals are performed by comparing QT, QTc and Delta QTc values that are calculated using LabWindows/CVI and the values that are displayed in MindrayuMEC 10 Multiparametric Monitoring unit. Initially, the same QT database is fed to both LabWindows/CVI and MindrayuMEC 10 unit. The uMEC 10 unit averages and displays the QT, QTc and Delta QTc values for every 60sec. Hence, the QT interval values which are calculated using LabWindows/CVI are also averaged over 60sec for the purpose of comparison and the corresponding percentage of accuracy is calculated. The Figure10 includes the numeric boxes which displays the QT interval, Delta QTc and QTc interval calculated by using Bazett, Fridericia, Hodges and Framingham formulae for the QT database - Sel310.

Figure 10. Calculated QT, QTc and Delta QTc values for the QT database - Sel310

The MindrayuMEC 10 unit displays the QT interval, Delta QTc and QTc interval calculated by using Framingham formulae for the QT database – Sel310 as shown in Figure11. The QT interval values which are obtained using LabWindows/CVI and MindrayuMEC 10 unit are compared for the calculation of accuracy.

Figure 11. QT, QTc and Delta QTc values displayed in MindrayuMEC 10 monitor for the QT database - Sel310
6.8 Overall Performance Evaluation of the QT Interval Measurement Algorithm

The overall performance evaluation of the QT interval measurement algorithm is as shown in the Table 2. The accuracy of R peak detection for 50 records of QT database is 98.48%. The accuracy of R peak detection for 20 records of MIT-BIH database is 93.54% and the overall accuracy of QT interval measurement algorithm for 20 records of QT database is 96.73%.

| Ecg Feature | Database                     | Number of Records | Accuracy (%) |
|-------------|------------------------------|-------------------|--------------|
| R Peak      | QT Database                  | 50                | 98.48        |
|             | MIT-BIH Arrhythmia Database  | 20                | 93.54        |
| QT Interval | QT Database                  | 20                | 96.73        |

7. Conclusion and Future Scope

Initially, raw ECG signals are preprocessed to remove power line interference by using an FIR band stop filter with a cut off frequency of 40-60Hz. R peaks are detected by using Pan Tomkins algorithm. Based on the valid R peak position Q peak and Q onset points are detected. T peak and T offset points are detected based on RR interval. QT interval is calculated by using the detected Q wave onset and T wave offset points. QT interval is corrected using different QTc formulae. Finally, ΔQTc is calculated. The entire process of QT interval measurement is implemented in LabWindows/CVI 2012 SP1 and the algorithm achieved an accuracy of 96.73% for QT interval measurement.

The future work mainly focuses on improving the accuracy of QT interval measurement by using different methods for the detection of Q onset and T offset points. This work may be also improved by using different classifiers for the classification of long QT syndrome and short QT syndrome.

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