Automated QT Interval Measurement from Multilead ECG Signals

D Hayn, A Kollmann, G Schreier

ARC Seibersdorf research GmbH, Graz, Austria

Abstract

This paper presents an algorithm for automated QT interval assessment, developed on several databases that provide expert annotations for QRS onset and T offset locations: The PhysioNet QT Database, the CSE Multilead Database, and the PTB Diagnostic ECG Database. The latter was also used for validating the algorithm by taking part in the Computers in Cardiology Challenge 2006.

After QRS detection, the QT interval was calculated for each single heart beat of each signal based on a previously developed algorithm. First the QRS onset and T offset were found coarsely for each channel, thereafter exact point detection was applied based on the coarsely found points and finally the results from different channels were combined.

We achieved a score of 16.34 when participating in the Computers in Cardiology Challenge 2006, which was the best result of all participants.

1. Introduction

The QT interval is defined as the time interval from the beginning of the depolarisation of the ventricles – represented by the QRS complex within the ECG – and the end of the repolarisation which is represented by the T wave in the ECG. It is a well established parameter in clinical diagnostics. QT prolongation favours cardiac arrhythmias and, therefore, it is an important cardiac risk factor. It is well known that some drugs can lead to QT prolongation. Several agencies require that newly developed drugs have to study the effect of the drug on the QT interval during clinical trials [1-3].

QT prolongation results from an increased action potential duration of the ventricular myocardium. It may be caused by congenital defects that prolong the APD, by drugs or by other cardiomyopathies. It results from a misbalance in one or more transmembrane currents, especially the potassium and sodium currents [4,5]. The short QT syndrome, on the other hand, is an inherited syndrome caused by genetic defects. It is accompanied by a high risk of ventricular tachycardia and ventricular fibrillation, especially in infants, children and young adults, caused by a misbalance in the potassium currents [4].

Automated assessment of the QT interval from the ECG is currently state of the art. Many ECG recording systems from several manufactures have implemented a QT measurement unit. Nevertheless, these measuring devices are often not very reliable. Especially in the case of abnormal T wave morphologies they often fail in correctly measuring the QT interval.

Several approaches for QT measurement are described in literature [6-10]. More than 30 institutes taking part at the Computers in Cardiology 2006 were developing algorithms for exact QT interval assessment in 2006. Nevertheless, up to now none of all these methods is able to measure the QT interval with sufficient accuracy.

2. Methods

QT interval assessment comprised of detection of the onset of the QRS complex, detection of the offset of the T wave, and calculation of the time interval in between QRS onset and T offset. The most crucial one of these three tasks was the detection of the offset of the T wave. Therefore, most of the programming and optimization work was spent on this topic. Yet, the algorithm described in the present article also detected the onset and offset of the P wave, the QRS complex and the T wave, as well as the corresponding peak values (P, Q, R, S, R' and T).

2.1. Characteristic Points Detection

The algorithm has initially been developed using the PhysioNet QT Database (QT-DB) [11]. In a first enhancement it was adapted to the signals of the CSE Multilead Database (CSE-DB) [12]. The original algorithm has been published in [13,14]. Meanwhile the algorithm has been extended in order to deal with different kinds of ECGs from various ECG databases.

Before detecting the characteristic points, QRS complex markers had to be available. The signal was split into single heart beats and for each beat the characteristic points were detected separately. Detection of onset, peaks, and offset of the P wave, QRS complex, and T wave for each beat was performed in two major steps: First, onset and offset points were detected for each channel separately. Thereafter the onsets and offsets found from the different channels were combined, leading to one onset and one offset for P, QRS and T per beat.

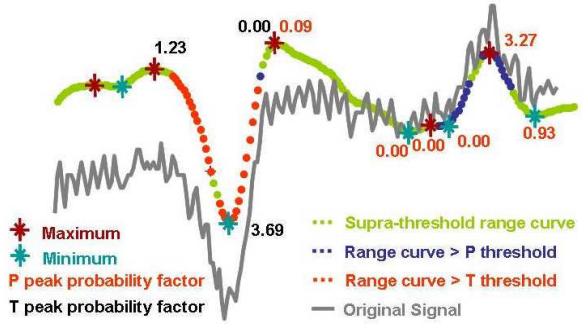

Figure 1. Coarse T offset detection. Grey line: Original ECG in between two QRS complexes. Colored line: Filtered ECG. The color encodes the level of the range curve. For each extremum situated within the possible time window for the T wave the probability factor for this extremum to be the T peak is plotted in black. Similarly the P peak probability factor is shown in red. The peaks with the highest probability factors were chosen as T and P peak, the neighboring extrema were used as the coarse onset and offset points.

2.2. Single lead wave detection

2.2.1. QRS Onset Detection

The signal right around each QRS complex was filtered, using a 60Hz low pass filter. The ranges (max minus min) of the filtered signal amplitudes within a short time window that was pulled over the signal, were calculated (range curve) and compared to a threshold value. The first supra-threshold value right before the QRS complex was chosen as QRS onset.

Detection of the exact point was done by stepwisely decreasing the threshold value. For each step a possible onset point was calculated and the mean range curve value right before and right after this possible point was determined. The point with the lowest ratio in between these mean values was chosen as the exact onset point.

2.2.2. Coarse T Offset Detection

The time window, within which the algorithm tried to find T offset, was obtained from the QT-DB. The longest and the shortest QT interval as well as the longest and the shortest corrected QT interval according to Bazett from all annotated beats of the QT-DB were calculated. Since the QT-DB consisted of a very broad range of ECGs from patients with various pathologies, it was considered, that all possible QT intervals were present within the QT-DB. Based on these intervals, the minimal possible time window was calculated for each beat.

The signal in between two consecutive QRS complexes (from QRS offset of one to QRS onset of the subsequent beat) was filtered with a bandpath filter. All local maxima and minima of the filtered signal were detected. One extremum was expected to be the T peak and one the P peak. Like for the QRS onset detection, the ranges of the signal amplitudes within a 40ms time window were calculated. These ranges were compared with one threshold value for the T wave and another for the P wave. The final extremum selection was based on:

- The ratio in between the number of super- and supra-threshold values in between the analyzed and the preceding extremum (gradient of the ascending wave).
- The gradient of the descending wave (calculated as for the ascending wave).
- The ratio in between super- and supra-threshold values before the preceding and after the subsequent extremum (stability of the signal outside the wave).
- The distance in between preceding and subsequent extremum (length of the wave)
- The difference in between the amplitude of the peak and the mean amplitudes of the subsequent and preceding extremum (amplitude of the wave).

Due to the high highpass cut-off frequency, T offset was represented by an extreme value within the filtered signal. Therefore, the coarse T offset point was selected as the subsequent extremum after the T peak.

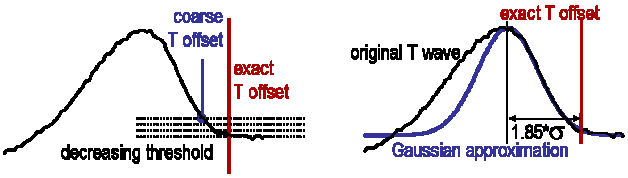

Figure 2. Exact T offset detection. Two independent methods for exact wave boundary calculation were used and averaged: Left: decreasing thresholds for the range curve. Right: Gaussian approximation to the descending T wave.

2.2.3. Exact T Offset Detection

After this coarse wave detection two independent methods for finding the exact T offset were used:

- The most distinct change in the range curve right around the coarsely found point – as described for the QRS onset detection – was detected.
- The T wave was approximated by a Gauss curve and the offset value was defined as the location of the maximum plus 1.85 times the sigma value of the Gauss curve.

While calculation of the exact QRS onset and QRS offset was done using the first of these methods only, the final onsets or offsets for P and T were obtained by averaging the results of both methods.

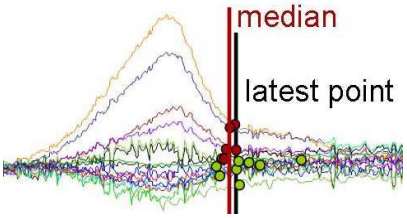

Figure 3. Combination of the results from different channels. The method is illustrated for the offset of the T wave. The points represent the offset points as found for each single channel separately. Green points were ignored due to low confidential parameters. Either the latest or the median of the remaining red points was chosen as the final T offset.

2.3. Lead consolidation

A measure was calculated for each point of each channel that indicated the credibleness of that point (confidentiality parameter). This parameter depended on: the probability factor calculated during coarse wave detection, the probability factor of the extreme values not chosen, the ratio of the mean amplitude of the range curve directly before and right after the onset or offset point, the behavior of the exact point detection (e.g. the final error estimate of the Gauss approximation) and on any kind of uncertainty that appeared during point detection, such as noisy signals, more than one possible points and so on.

If there were two channels only, the final point was obtained by weighting the points from different channels with their confidential parameter and calculating an average value. For more channels the algorithm ignored all channels with a confidential parameter that was less than 1/30 times the maximum confidential parameter of all channels. Version 1 of the algorithm chose the median of the remaining points. In version 2 the earliest (for wave onset) or latest (for wave offset) point of the remaining channels was chosen as the final wave boundary. If the remaining points were not within a certain time window (75ms), the median of the remaining values was chosen in any case in order to get a less exact but more stable result.

2.4. First representative beat selection

The first beat situated more than 300ms from the beginning of the signal, whose QT interval differed less than 20ms from the median of all QT intervals and whose QRS morphology was similar to the morphology of the majority of QRS complexes within the signal was selected. If no such point was found within the first 5 seconds, the signal was rejected.

3. Results

Table 1 shows the results that had been achieved when comparing our algorithm to different references. All results were achieved using version 1 of the algorithm (median) for combining the results from different leads.

The score of the Computers in Cardiology Challenge 2006 was calculated as the root mean squared differences in between calculated and reference QT intervals divided by the sensitivity of the algorithm. We achieved a score of 16.34. The sensitivity was 95%.

Table 1: Distance in between algorithm results and references. Mean value [ms] ± standard deviation [ms] (sensitivity [%]) are shown for three different references.

	QT-DB	CSE-DB Experts	CSE-DB Algorithms.
Pon	1.4 ± 28.3	-25.0±19.0	-20.2±21.6
Poff	10.0 ± 25.2	6.2±5.7	8.68±15.97
QRSon	7.52 ± 12.60	-5.0±15.6	-2.3±6.8
QRSoff	5.7 ± 15.1	-6.5±6.0	-5.6±4.7
Ton	-1.4 ± 45.8	n.a.	n.a.
Toff	2.8 ± 34.9	-11.9±19.2	-3.8±11.8

4. Discussion and conclusions

The algorithm presented was initially developed and optimized using the QT-DB only. The QT-DB consists of ECGs with two leads. In the initial version of the algorithm, lead consolidation was done with version 1 (median).

Thereafter, the algorithm was validated with the CSE-DB. Some settings and a few source code lines had to be adapted, since e.g. the ECGs of the CSE-DB contain 15 channels and were recorded with a different sample frequency. However, methodical changes were not made. The results achieved with this unmodified algorithm were rather poor: Onset points were found to be too late, offset points too early. This resulted in a high mean deviation in between expert and algorithm annotations while the standard deviations performed quite well.

The algorithm was adapted in order to reduce these systematic deviations. It has been shown in an earlier study [10] that automated algorithms tend to situate onsets later and offsets earlier than experts. Therefore, the latest-point-method (version 2) for lead consolidation was introduced. Using this adapted algorithm low mean and standard deviations in between the algorithm's results and the expert annotations could be achieved for both, the QT-DB and the CSE-DB.

When in spring 2006 the topic of the Computers in Cardiology Challenge 2006 was announced our algorithm was used to take part at the challenge. An initial entry was sent to the organizer of the challenge, and the score we received was rather disappointing. Unfortunately no additional information about the error was available. But – knowing that the reference values of the challenge were

achieved by averaging the results of all participants – it was assumed that the bad score was due to systematically too late T offset values. So, the algorithm was re-designed by going back one step again: Instead of the latest-point-method the median (version 1) was used again. Suddenly, the score improved dramatically, and the result of our algorithm was better than those of all other participants who tool part in the challenge.

The results presented here were all achieved using this final algorithm. Therefore, the deviations to expert annotations are rather large, compared to results presented in previous papers [13,14] and other publications [6-10].

Though the latest-point method seemed to fit closer to physicians annotations, there were some arguments for returning to the median method again. The first – of course – was the Computers in Cardiology Challenge. Additionally, the averaging method, though less exact, was more stable than the latest-point-method since it was less susceptible on outliers. Though this susceptibility could be reduced by eliminating points with low confidential parameters, it still sometimes happened that wrongly found points were selected for T offset.

Thinking of QT interval control during clinical trials for newly developed drugs, it may not be necessary to achieve high precision in terms of the absolute value of the QT interval. In many cases it may be enough to detect changes in the QT interval reliably. And relative changes over time can be detected by both methods similarly. On the other hand, QT interval measurement algorithms are expected to achieve similar results as physicians. And the QT intervals calculated with the latest-point-method correlate closer to QT intervals measured by physicians than the intervals calculated with the averaging method.

The most difficult part of the characteristic point detection is the detection of the points for each single lead. Lead consolidation is a rather simple task. Therefore, the results achieved with the presented algorithm are mostly depending on the single lead point detection. And single lead point detection has hardly changed – neither when adapting the algorithm to the CSE-DB nor during the PhysioNet Computers in Cardiology Challenge 2006.

References

[1] Medicines Agency . ICH Topic E 14 - The Clinical Evaluation of QT/QTc Interval Prolongation and Proarrhythmic Potential for Non-Antiarrhythmic Drugs - Step 5 – Note for guidance on the clinical evaluation of QT/QTc interval prolongation and proarrhythmic potential for nonantiarrhythmic drugs (CHMP/ICH/2/04).2005.

[2] U.S. Department of Health and Human Services Food and Drug Administration, Center for Drug Evaluation and Research (CDER), and Center for Biologics Evaluation and Research (CBER). E14 - Clinical Evaluation of QT/QTc Interval Prolongation and Proarrhythmic Potential for Non-Antiarrhythmic Drugs.2005;, Guidance for Industry.

[3] Japan's National Institute of Health Services. Draft Consensus Guideline - The Clinical Evaluation of QT/QTc Interval Prolongation and Proarrhythmic Potential for Non-Antiarrhythmic Drugs - E14.2004; Released for Consultation at Step 2 of the ICH Process on 10 June 2004 by the ICH Steering Committee.

[4] Antzelevitch C. Cardiac repolarization. The long and short of it. Europace 2005;7 Suppl 2:3-9.

[5] Antzelevitch C. Role of transmural dispersion of repolarization in the genesis of drug-induced torsades de pointes. Heart Rhythm. November 2005; 2(2 Suppl):S9-15

[6] Martínez JP, Almeida R, Olmos S, Rocha AP, Laguna P. A wavelet-based ECG delineator: evaluation on standard databases. IEEE Trans Biomed Eng 2004;51(4):570-581.

[7] Batchvarov V, Yi G, Guo X, Savelieva I, Camm AJ, Malik M. QT interval and QT dispersion measured with the threshold method depend on threshold level. Pacing Clin Electrophysiol 1998;21(11 Pt 2):2372-2375.

[8] Savelieva I, Yap YG, Yi G, Guo X, Camm AJ, Malik M. Comparative reproducibility of QT, QT peak, and T peak-T end intervals and dispersion in normal subjects, patients with myocardial infarction, and patients with hypertrophic cardiomyopathy. Pacing Clin Electrophysiol 1998;21(11 Pt 2):2376-2381.

[9] Laguna P, Jané R, Caminal P. Automatic detection of wave boundaries in multilead ECG signals: validation with the CSE database. Computer and Biomedical Research 1994;27(1):45-60.

[10] Willems JL, Arnaud P, van Bemmel JH, Bourdillon PJ, Brohet C, Volta SD, Andersen JD , et al. Assessment of the performance of electrocardiographic computer programs with the use of a reference data base. Circulation 1985;71(3):523-534.

[11] Open database:
The QT Database [database on the Internet]. Cambridge (MA): PhysioNet. [cited 2006 Aug 27]. Available from : http://www.physionet.org/physiobank/database/qtdb/

[12] Recommendations for measurement standards in quantitative electrocardiography. The CSE Working Party. Eur Heart J 1985;6(10):815-825.

[13] Hayn D, Schreier G, Lobodzinski S. Development and evaluation of a QT interval algorithm using different ECG databases. International Journal of Bioelectromagnetism 2003;5:122-123.

[14] Schreier G, Hayn D, Lobodzinski S. Development of a new QT algorithm with heterogenous ECG databases. J Electrocardiol 2003;36 Suppl:145-150.

Address for correspondence

Dieter Hayn
Reininghausstr. 13/1, 8020 Graz, Austria
dieter.hayn@arcsmed.at