Performance of a Continuous Real-Time QT Interval Monitoring Algorithm for the Critical-Care Setting

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Abstract

We developed an automated continuous real-time QTc interval monitoring algorithm for the critical-care setting. The performance of the QT interval measurement algorithm was tested on the PhysioNet adult QT ECG dataset (n=105), and on a pediatric ECG dataset (n=20) and a neonatal dataset (n = 24) recorded from intensive care units. The algorithm performance is measured by sensitivity (the ability to measure the QT interval), and accuracy (the difference between the automated QT measurements and cardiologists' manual annotations). We obtained 92% sensitivity in the adult group, 85% in the pediatric group and 75% in the neonatal group. On the 95 adult cases which had both an algorithm and a cardiologist measurement, the mean difference was 1 ms with a standard deviation of 35 ms. On the pediatric ECGs, the mean difference was -12 ms with a standard deviation of 20 ms. In the neonatal cases, the mean difference was -6 ms with a standard deviation of 12 ms.

1. Introduction

The American Heart Association has recently endorsed a practice standard for ECG monitoring of critical care patients which includes a recommendation for QTc interval surveillance for patients taking potentially proarrhythmic medications [1]. Current hospital practice in the critical care setting is usually manual measurement of QT (and RR interval for QTc computation) on a single beat by the clinical staff once per 8-hour shift or per day. This practice is problematic due to the beat-to-beat variability of both repolarization and manual measurement accuracy, and may lead to missed or false positive detections of QT prolongation. We have created a continuous real-time QT and QTc interval monitoring algorithm to meet this clinical need [2]. The current paper focuses on the performance of this real-time QT interval monitoring algorithm.

2. Study Population

The PhysioNet QT dataset used for the adult study population is a publicly available database which has been annotated by cardiologists for QT interval [3]. This dataset consists of 105 cases, each 15 minutes long with two ECG channels. It contains a variety of T wave morphologies in cases chosen from the MIT-BIH arrhythmia, supraventricular arrhythmia, long-term, and ST change, BIH normal and sudden death, and European ST-T databases [4].

In addition to the PhysioNet QT dataset, pediatric 2-channel ECGs (n = 20) were recorded in a pediatric intensive care unit (PICU) from patients aged 2 weeks to 15 years old, and single-channel neonatal ECGs (n = 24) were recorded in a neonatal intensive care unit (NICU) from newborns to 2 week old patients.

3. Methods

The ECG signal from patients being monitored in the critical care setting contains significant amounts of muscle and motion artifacts, and the locations and number of electrodes varies widely. The real-time QT interval measurement algorithm was designed to address these challenges. The algorithm is divided into several steps. The first step is to form an averaged beat for each lead in each 15-second time window from tightly clustered normal beats. The use of clustering rejects artifact, and signal averaging reduces noise. In the second step, the averaged beat waveforms from all leads are combined using a root-mean-squared (RMS) formula to compute a single RMS ECG waveform. Using an RMS waveform reduces the effects of respiratory axis shift and patient positional changes and allows for identification of earliest Q wave onset to latest T wave offset. Q onset and T offset are determined using a novel measurement technique [2,5,6]. For T wave offset, if the RMS ECG T wave amplitude is above a threshold, a virtual line is drawn from the peak of the T wave to a heart-rate adjusted point after the T wave. The point along the ECG waveform with the maximum vertical distance from this line is determined to be the T offset. For Q onset, the line

is drawn from the R wave to a heart-rate adjusted point prior to the QRS complex. If T wave amplitude is too low, no algorithm measurement is made. Next, the QT interval is computed, and a short-term heart-rate is used for computation of QTc. Finally, each minute, four 15-second QT and QTc value pairs are examined, and one pair is chosen as the representative values for the minute. An example time series of the algorithm generated QT interval values is shown in Figure 1.

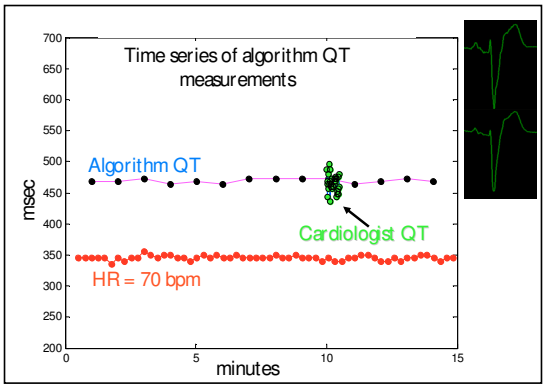

Figure 1. Example time series of 1-minute algorithm QT measurements passing through cluster of cardiologist beat-by-beat QT measurements.

4. Results

The continuous QT monitoring algorithm is measured quantitatively by sensitivity and accuracy.

The algorithm sensitivity reflects the algorithm's ability to produce QT interval measurements on a given ECG. Table 1 shows the average heart rate for the three databases, the number of cases annotated by the cardiologist, and the number and percent of cases in which a QT interval measurement was made by the algorithm in the vicinity of the cardiologist annotations.

In the PhysioNet QT dataset, the cardiologist(s) deemed that 103 cases could be annotated for QT intervals. Similarly, the QT algorithm does not make measurements when consistent beat morphology is not found, or when the T wave amplitude is too low and below a threshold. Thus, in a computation of "measurement" versus "no measurement" against the cardiologist annotations, the algorithm sensitivity was 92% (Table 1). Algorithm measurements were made in 85% of the PICU cases, and in 75% of the very noisy NICU cases.

Cardiologist annotations were used as the "gold standard" reference QT values in the study. In 103 out of 105 records of the PhysioNet QT dataset, both Q onset and T offset have been annotated for approximately 30 to 50 beats starting from the 10th minute by one and occasionally two cardiologists viewing both leads. Thirteen cases from the PhysioNet QT dataset that either had large difference between the two annotating cardiologists or were annotated inconsistently with regard to T versus U waves were re-annotated by the cardiologists who annotated the pediatric and neonatal cases. For the pediatric and neonatal ECG sets, two cardiologists annotated QT intervals in a 15-second period starting from the 7th minute of the recording.

Table 1. Algorithm Sensitivity: percent of cases that had an algorithm measurement in the vicinity of the cardiologist annotations in PhysioNet (n = 103), PICU (n = 20) and NICU (n = 24) QT datasets.

	Mean HR	N	Number Measured	Percentage
PhysioNet	71	103	95	92%
PICU	123	20	17	85%
NICU	155	24	18	75%

For each case, the mean values of the manual measurements i.e., the average of all beats from one or both (if present) cardiologists were used as the reference QT interval in the testing.

The algorithm measurements used in the comparison were the average of the algorithm's 1-minute QT measurements for each case that fell within a window starting slightly before the first beat of the cardiologist annotation and ending slightly after the last beat of cardiologist annotation.

On a case-by-case basis, the average algorithm QT interval was compared to the average cardiologist QT interval. The mean and the standard deviation (SD) of the difference were computed (Table 2), and the pairs were fitted with a linear regression model (Figures 2,3,4).

Table 2. QT Accuracy: algorithm QT minus Cardiologist QT for cases that had both cardiologist annotations and algorithm measurements.

	N	Mean Diff. (ms)	Std Dev (ms)
PhysioNet	95	1	35
PICU	17	-12	20
NICU	18	-6	12

On the 95 cases in the PhysioNet QT dataset that had both an algorithm and a cardiologist measurement, we obtained a mean difference of 1 ms with a standard deviation of 35 ms. The mean difference on the pediatric data is -12 ms with a standard deviation of 20 ms. The mean difference in the neonatal dataset is -6 ms with a standard deviation of 12 ms.

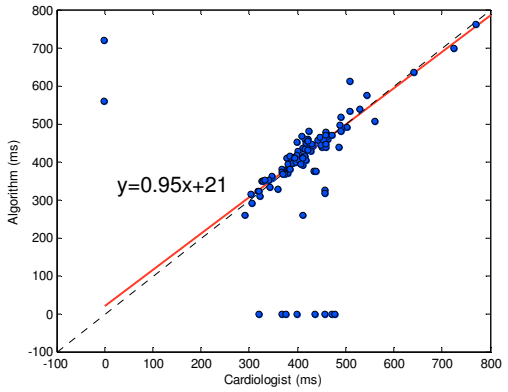

Figure 2. Algorithm accuracy tested on the PhysioNet QT Database. Cardiologist QT (x-axis) vs. algorithm QT (y-axis). Cases with no matching algorithm or cardiologist value are shown along the axes. Regression slope=0.95.

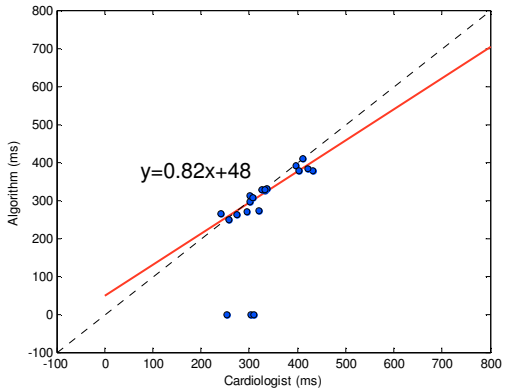

Figure 3. Algorithm accuracy tested on PICU dataset. Cardiologist QT (x-axis) versus algorithm measured QT (y-axis). Regression slope=0.82.

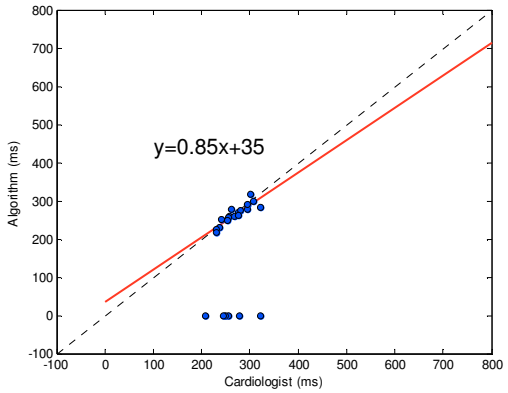

Figure 4. Algorithm accuracy tested on NICU dataset. Cardiologist QT (x-axis) versus algorithm measured QT (y-axis). Regression slope=0.85.

Least-squares linear regression was used to show the relationship between the algorithm QT values and the cardiologist QT values, when measured by both. The resulting regression line has a slope of 0.95 for the PhysioNet dataset (Figure 2), which is very close to the desired identity line; for the PICU dataset, the slope is 0.82; on the NICU data the slope is 0.85. The residual case order plot (Figure 5) for the PhysioNet dataset shows the 95% confidence intervals on the regression model errors. Four cases fell outside the interval.

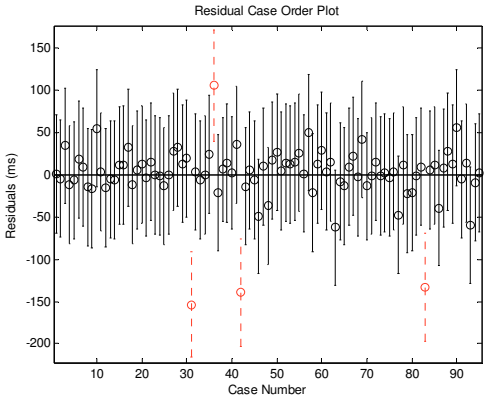

Figure 5. PhysioNet dataset linear regression residuals with 95% confidence intervals. Four cases (dotted) fall outside the 95% confidence interval.

The Bland-Altman plot for the PhysioNet dataset shows the algorithm minus cardiologist measurement differences versus the mean of the cardiologist and algorithm QT values. The relatively flat regression line through the error data shows that the differences are randomly distributed, with no real trend versus QT value (Figure 6).

5. Discussion and conclusions

The algorithm approach which computes the RMS ECG and measures QT interval on this waveform rather than on the individual leads has proven to be an effective choice. We are in agreement with Lux et al. that measuring RMS ECG is more robust than measuring the ECG of an individual lead [9]. More importantly, the RMS ECG provides a global QT interval which is more meaningful than the localized QT interval reflected in one or two leads. As pointed out by Lux et al. the number of leads may modify the morphology of the RMS ECG, but it does not significantly alter the timing of QT onset and offset. The advantages of using RMS ECG have been shown and this technique has been widely adapted in QT research [10,11].

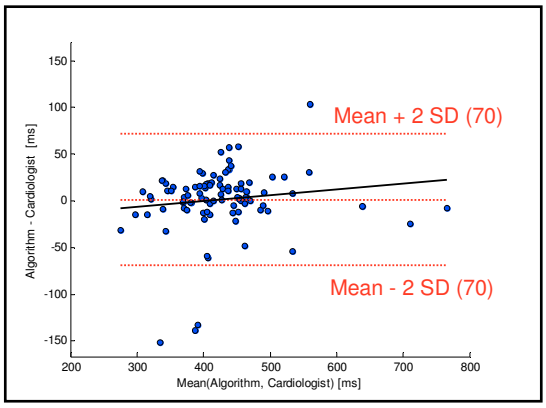

Figure 6. Bland-Altman plot shows the measurement difference versus mean of the cardiologist and algorithm QT measurements in the PhysioNet QT dataset. Dashed horizontal lines indicate mean difference and mean +/- 2 standard deviations. The regression line shows relatively little trend of the error vs. QT value.

ECG monitoring in the pediatric and neonatal critical-care setting is common and real-time QT monitoring is clearly a must [12,13,14]. However, neonatal ECG monitoring is usually done using a single lead which often contains significant artifact and noise due to unrestricted movements and crying. Since no previous computerized QT studies in the neonatal population have been reported, we were not sure what to expect with regard to the QT monitoring algorithm performance. The sensitivity of 75% and accuracy of -6 ± 12 ms obtained in the neonatal dataset is quite respectable considering analysis occurred on single lead ECGs with severe noise.

In addition to having tested the annotated QT datasets from adult, pediatric, and neonatal populations, we have also stressed the QT algorithm by testing on a variety of arrhythmia, extremely noisy, paced, and long term ECG recordings. The results obtained show a good level of algorithm sensitivity, noise rejection, stability, and the ability to track changing QT intervals with less variation than error-prone single-beat measurements.

We conclude that real-time QT interval monitoring is possible and should be adopted, and that an automated algorithm has been developed which provides accurate and robust QT surveillance. Our algorithm permits automated QT and QTc monitoring not only for adults but also for children and newborn babies in the critical-care setting.

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