A Real-time ST-segment Monitoring Algorithm Based on a Multi-channel Waveform-Length-Transform Method for Q-onset and J-point Detection

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Abstract

In the paper, we present a fully automated real-time multi-lead ST-segment monitoring algorithm. For a representative normal beat in each ST measurement interval, the ECG leads with low signal quality are excluded and the remaining leads are used in a multi-lead waveform-length transformation to form a length signal for Q-onset (Q) and J-point (J) determination. From Q, the isoelectric point is determined and used with the J to measure the ST-segment at J or J plus an offset for all available leads. A development set of 158 records and a test set of 60 records with cardiologists' beat-by-beat Q and J annotations were used to develop and evaluate the Q and J detection. The ESC ST-T Database and a 60-patient annotated 12-lead PTCA dataset were used to evaluate the algorithm's ST performance. Detailed statistical results are given in the paper. The test results demonstrate that the described ST-segment monitoring algorithm is effective and reliable.

1. Introduction

Real-time ST-segment monitoring of multi-lead electrocardiogram (ECG) signals, which allows for continuous detection and tracking of myocardial ischemia, provides a valuable clinical tool for cardiac patient management. The ST-segment is measured as the voltage difference between the J-point (J) or J plus an offset and the isoelectric point (Iso). The Iso is typically located between the P- and Q-waves (the P-R segment) or in front of the P-wave (the T-P segment).

The Iso and J points may be manually obtained, e.g., by subtracting a time interval from the QRS peak (R) and adding a time interval to R, respectively; and these fixed time intervals are visually decided for each patient, usually at the beginning of the ECG monitoring.

In the automated approach, one way to determine the Iso and J is by searching their direct features of the P-R segment and QRS offset, within predefined windows, from computer-detected QRS peak, on each ECG lead [1,2]. This lead-by-lead direct searching for (and resolving of the 'global') Iso and J points [2] was time-consuming, and the results could be corrupted if any lead has an unusual QRS morphology or local noise.

Another way to obtain the Iso and J is through detection of the QRS onset (Q) and the offset (J), as the Iso can be reliably derived from Q by subtracting a known time interval. In this paper, we present a fully automated real-time ST monitoring algorithm where the Q and J are determined based on a multi-lead ECG waveform-length-transformation (WLT) method [3] with a lead-selection process based on signal quality assessment (SQA). In this method, all available ECG leads with good signal quality for the considered normal beat are transformed into a single-channel combined waveform length signal (CWLS), on which the Q and J are determined. This method does not require lead-by-lead search and directly provides the "global" Q and J points, thus it is simple and efficient. Independent reference datasets with cardiologists' beat-by-beat Q and J annotations were used to develop and evaluate the algorithm's Q and J detection performance. The ESC ST-T database and an annotated 12-lead PTCA (percutaneous transluminal coronary angioplasty) ECG dataset were used to evaluate the algorithm's ST monitoring performance. Results show that the described real-time ST monitoring algorithm is effective and reliable.

2. Materials and methods

2.1. Datasets

The development dataset for the Q and J detection algorithm consists of 158 records, including 105 records from the Physionet QT-Database [4], 23 records selected from the MIT-BIH Arrhythmia Database [5], and 30 records selected from a PTCA database. Each record in the QT Database has 15-miniute, 2-channel ECG signals sampled at 250Hz with amplitude resolution of 5μV/lsb, and the reference pQRSt (P-wave onset and offset, QRS onset and offset, and T-wave end) annotations were made by one or two cardiologists starting at around minute 10 for about 30 seconds. The 23 records selected from the MIT-BIH arrhythmia Database have a variety of beat

types including normal, PVC (premature ventricular contract), LBBB and RBBB (left and right bundle branch block), and AF (atrial fibrillation) beats; each record has 30-minute 2-channel ECGs resampled to 500Hz with resolution of 5μV/lsb The reference Q and J annotations were made by cardiologists and experienced biomedical researchers starting at minute 10 for 60 seconds. We obtained 60 records of 12-lead ECGs from adult patients who underwent elective PTCA procedure. These records range from 2 to 16 minutes in length, and were down-sampled to 500Hz from their original sampling rate of 2000 Hz; the amplitude resolution is 0.6μV/lsb. Each of the PTCA records has two sections of 1-minute cardiologists' annotated Q and J references: a) the ST baseline region (before balloon inflation); and b) the ST change region (during peak balloon inflation). Half ($PTCA^d$) of the 60 annotated PTCA records were included in the development set.

The test set for the Q and J detection algorithm contains 60 annotated ECG records, which includes the remaining half ($PTCA^t$) of the above 12-lead PTCA records, and 30 2-channel ECG records from the AHA Database selected for their representative normal and abnormal (e.g. PVC) beats. Each of the 30 AHA records is 35-minute in length and was sampled at 250Hz with amplitude resolution of 2.5μV/lsb. The 60-second Q and J annotations were made by cardiologists on each record at minute 10, except when this region was not suitable and an earlier or a later time would be used.

For evaluation of the algorithm's ST measurement performance, both the 90-record ESC ST-T Database [6] with annotated ST measurements at J+80ms and the 60-record PTCA dataset were used. To obtain the reference ST measurements for the 12-lead PTCA dataset, we derived the ST measurements at J by taking the voltage difference between the annotated J and the Iso located at 20ms prior to the annotated Q.

For results comparison, we also manually set the Iso and J points from the R peak, for each of the 90 ESC ST-T Database records, by visually identifying the Iso-to-R and R-to-J intervals of each individual ECG record. These manually set Iso and J points are used to calculate the ST measurement at J+80ms for comparing results obtained from the automated algorithm.

2.2. The algorithm

A block diagram of the ST monitoring algorithm is shown in Figure 1. For a given normal (or representative normal) beat, assuming its N-lead ($N \geq 1$) beat-cycle ECG waveforms are available. For each lead of the ECG waveforms, a signal quality assessment (SQA) is applied. The SQA assesses the signal quality of the lead, in terms of its noise level and QRS amplitude, and labels the lead as 'acceptable or 'unacceptable'. The SQA acts like an on/off switch, allowing the ECG lead to be included in the WLT process only if the lead is deemed acceptable.

Those M leads ($0 \leq M \leq N$) considered having good signal quality are then used by the multi-channel WLT component to form a combined CWLS. The Q and J points are then determined from the CWLS using a set of decision rules. Finally, for each lead, the ST measurement is calculated as the voltage difference between the isoelectric level determined from the Q and the voltage at J or J + offset.

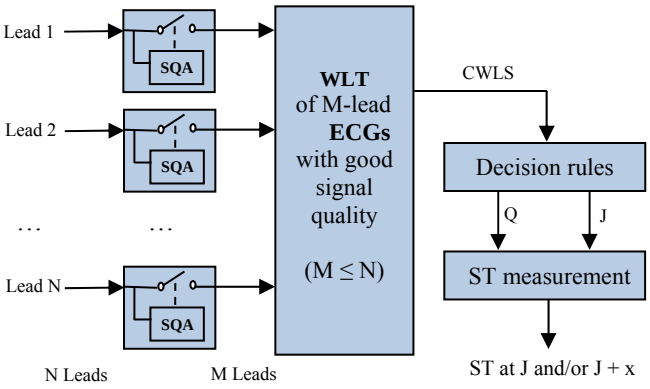


Figure 1. Structure diagram of the ST monitoring algorithm based on Q and J detection using the multi-channel WLT method with lead selection.

Signal quality assessment: Three features, high-frequency noise (HFN), low-frequency noise (LFN), and QRS amplitude, are used to assess the ECG signal quality for each lead. The HFN is measured by summing the 2nd-order difference of the beat-cycle ECG waveform [7]. The LFN is calculated by summing the recursively-smoothed ECG in the beat-cycle window [7]. The thresholds for judging the HFN and LFN levels were empirically determined. The absolute QRS peak value was taken as the QRS amplitude, and the qualifying amplitude threshold was set to 0.4mV.

WLT for multi-lead ECGs: The multi-channel ECG WLT-based Q and J detection is an adaption of that described by Zong, et al [3]. For a beat marked by its QRS peak, R, the combined waveform length signal for the M ECG leads at sample i, $CWLS[i]$, is calculated in the region $[R-200ms, R+200ms]$, according to the following formula:

$$CWLS[i] = \sum_{k=i-w}^{i} \sqrt{\sum_{j=1}^{M} (C + \Delta y^2{}_{j,k})} \qquad (1)$$

where, $w = 144ms$, $\Delta y_{j,k} = ecg_j[k] - ecg_j[k-1]$,

$ecg_j[k]$ is the lead j ECG signal at sample k,

M is the number of leads, C is a constant.

The constant C in (1) is a scaling factor; its value was

experimentally chosen to properly scale the WLT to the QRS. According to the multi-channel ECG WLT theory [3], the ascendant section of the CWLS corresponds to the 'global' QRS duration from the available ECG channels. Figure 2 shows an example of 8-lead ECG waveforms and the resulting CWLS.

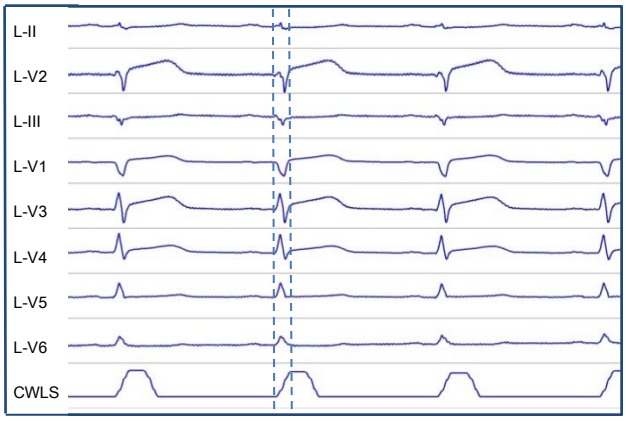


Figure 2: Example of the *CWLS* and 8-lead ECG signals

Determination of Q and J via CWLS: The Q and J points are determined according to the beginning and ending of the ascendant section in the CWLS, respectively; threshold and compensation based methods similar to those described in [3] were utilized.

ST measurement according to Q and J: The Iso-point was determined by subtracting 20ms from the detected Q. For each ECG lead of the considered normal beat, the isoelectric voltage was calculated by averaging the ECG samples in a 20ms-window centered on the Iso-point and the ST level at J + offset (e.g. 0, or 80ms) was calculated by averaging the ECG samples in a 20ms-window centered on the detected J + offset.

2.3. Evaluation process

For the Q, J detection, the algorithm was first developed using the 158-record development dataset on a beat-by-beat basis. Both the normal and abnormal beats were considered. Subsequently, the algorithm was tested using the 60-record test set, on a beat-by-beat basis, without any further algorithm adjustment. Both the normal and abnormal beats were also considered.

For the ST measurement, a beat detection and classification process was performed first by a beat detection and classification algorithm. The real-time ST-segment measuring interval was set to 15 seconds. For each 15-second interval, a representative normal beat was generated by averaging the selected dominant normal beats; and all available ECG leads of the representative normal beat were then processed by the ST algorithm, which produced ST measurements (at J + offset) for each of the ECG leads.

For the 90-record ESC ST-T Database, the algorithm's ST measurements (once per 15 seconds) at J+80ms were compared to the database ST references (cardiologists' annotation). We also performed the same analysis using the manually determined Iso and J points, for each ESC ST-T record.

For the 60-record PTCA dataset, the algorithm's ST measurements at J point (once per 15 seconds) were compared to the data references (averaged beat-by-beat ST values in each of the corresponding 15-second intervals).

3. Results

3.1. Performance of Q and J detection

Table 1 shows the Q and J detection results on the 158-record development dataset. The number of annotated beats (Ann-beats) and number of detected beats (Det-beats) are listed. Eight leads (II, III, and V1-V6) out of the 12 in the PTCA records were used for the Q and J detection. The performance is measured by mean difference (MD) ± standard deviation of the difference (SDD) (in ms) between the algorithm's result (test) and the cardiologists' annotation (ref). The 'gross' results are presented, i.e. each beat in each record is considered an event for the statistics. Note that all beat types including normal, PVC, and LBBB/RBBB, in the annotated dataset are considered.

Table 1. Q and J detection results on the development set

Data Set	#of Rec.	#of Ch.	Ann-beats	Det-beats	Q (in ms) (test - ref)	J (in ms) (test - ref)
QT	105	2	3615	3615	2.9 ± 12.3	4.8 ± 16.0
MIT	23	2	1805	1790	-5.0 ± 8.7	1.2 ± 10.1
PTCA[d]	30	8	4326	4325	-5.8 ± 6.6	-0.6 ± 15.2
Average:					-2.9 ± 9.4	1.6 ± 13.7

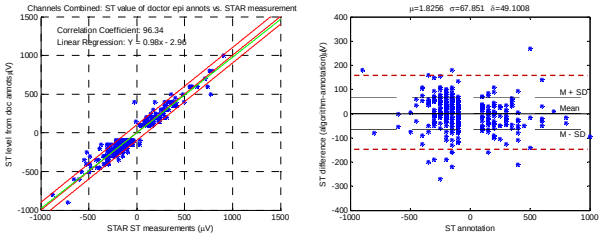
The Q and J detection performance on the test set is shown in Table 2. Eight leads (II, III, and V1-V6) of the 12-lead PTCA records are used. On average, the accuracy results in terms of MD ± SDD (ms) for Q and J are -2.7 ± 7.7 and 0.5 ± 10.5, respectively. Also, these are the gross results. Multiple beat types (such as normal and PVC) are considered.

Table 2. The Q and J detection results on the test set

Data Set	#of Rec	#of Ch	Ann-beats	Det-beats	Q (in ms) (test - ref)	J (in ms) (test - ref)
AHA	30	2	2537	2487	0.5 ± 10.0	-1.0 ± 12.7
PTCA[t]	30	8	4534	4528	-5.8 ± 5.4	2.0 ± 8.3
Average:					-2.7 ± 7.7	0.5 ± 10.5

3.2. Performance of ST measurement

Fig. 3 (a) is a scatter plot showing the ST measurements at J+80ms from the algorithm vs. the reference ST (at J+80ms) annotated by cardiologist, for both ECG channels of the ESC ST-T Database. The correlation coefficient (CC) and linear regression slope (LRS) are 96.3 and 0.98, respectively. The algorithm's ST performance measured in MD and SDD are 1.83μV and 67.9μV, respectively; Fig. 3 (b) is the Bland-Altman plot of the difference between the algorithm's results (test) and the reference.

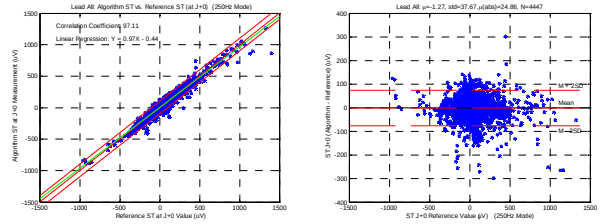


(a) (b)

Figure 3. ST at J+80ms results on the ESC ST-T Database: (a) Scatter plot of the algorithm results (test) vs. the reference; (b) Bland-Altman plot of difference between test and reference.

For comparison, ST measurement results at J+80ms using manually determined isoelectric and J points on the ESC ST-T database are 96.2, 0.99, 5.64μV, and 69.2μV, for CC, LRS, MD, and SDD, respectively. It is seen that the results from the algorithm based on the automated Q and J detection are as good as those obtained by manually setting of the optimal isoelectric and J points.

Fig. 4 (a) is a scatter plot showing the ST measurements at J from the algorithm vs. the reference ST (at J) for the 60 12-lead PTCA records. The CC and LRS are 97.1 and 0.97, respectively. The algorithm's ST performance measured in MD and SDD are -1.27μV and 37.7μV, respectively; Fig. 4 (b) is the Bland-Altman plot of the difference between the test and the reference ST measurements.



(a) (b)

Figure 4. ST at J results on the PTCA Database: (a) Scatter plot of the algorithm results (test) vs. the reference; (b) Bland-Altman plot of difference between test and reference.

4. Conclusion

We have presented a fully automated real-time ST-segment monitoring algorithm based on the Q-onset and J-points determined using the multi-lead ECG waveform-length-transformation method with SQA-lead-selection. In this method, the 'global' Q and J points are determined via a single-channel CWLS of the multi-lead ECGs and does not require lead-by-lead search for the Iso and J points. The SQA-based lead-selection process excludes ECG leads with poor signal quality thus enhancing the reliability of the ST measurements.

The test results using a variety of annotated databases have demonstrated that the fully automated ST monitoring algorithm is effective and reliable. For example, the algorithm's performance on the ESC ST-T Database is as good as the results obtained by manually setting the optimal Iso and J points for each record. Furthermore, the algorithm is also insensitive to QRS morphology changes which may occur during continuous patient monitoring.

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