Analysis of Transient ST Segment Changes During Ambulatory Monitoring

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Abstract

We describe a two-channel algorithm for robust automated detection of transient ischemic ST changes. The algorithm operates as a post-processor to the ARISTOTLE *arrhythmia detector. An ST segment deviation detection function is calculated as the magnitude of the ST segment vector determined from both leads. Using a variety of auxiliary functions, the algorithm distinguishes between transient ischemic ST changes and non-ischemic ST deviations caused by position-related changes in the electrical axis of the heart. A comprehensive evaluation of this algorithm using the European ST-T Database is presented elsewhere in these proceedings.*

1 Introduction

Analysis of ambulatory ECG recordings for ischemic ST segment changes is complicated by the occurrence of ST segment changes which are not related to ischemia. Non-ischemic ST segment changes may be caused by very slow drift of the ST segment level, but those caused by position-related changes in the electrical axis of the heart (axis shifts) are the most common and troublesome. Since such changes may cause significant shifts in the ST segment level and false detection of ischemia, it is important to identify these effects. A well-designed ST analyzer should distinguish between ischemic and non-ischemic ST changes.

Gallino *et al.* [1] reported a method for automated detection of ischemic ST episodes which is appropriate for quantification of ischemic episodes and better than visual observation; the method is very slow, however, and it does not include any technique for adjustment of reference ST level. An automated detector described by Shook *et al.* [2] differentiates "stable" from "unstable" segments of the recording, and corrects the reference ST level for non-ischemic deviations during the "unstable" segments.

Using the European ST-T Database [3] we have developed and evaluated a new two-channel algorithm for robust automated detection of ischemic ST segment episodes. The algorithm determines the onset, the end, and the maximum ST deviation of each detected episode automatically. It detects axis shifts and corrects the reference ST segment level to account for axis shifts as well as for very slow drift of the ST segment level. Since methodology for evaluating the performance of such algorithms using the European ST-T Database has not been published previously, we describe an evaluation protocol elsewhere in these proceedings, using the evaluation of the algorithm described in this paper as a case study [4].

2 Methods

The ST analysis algorithm processes two ECG signals with reference to beat labels produced by ARISTOTLE, an arrhythmia analyzer developed by the third author [5]. Recordings were initially low-pass filtered by a 6-pole Butterworth filter with a cut-off frequency of 55 Hz. A cubic spline baseline approximation and subtraction technique was used to remove baseline wander. The main features of the ST analysis algorithm are:

1. Construction of a sequence of average beats. Each average beat is derived from at least 16 normal beats over an epoch of at least 15 seconds. Ectopic beats, beats adjacent to ectopic beats, and noise-contaminated beats are excluded from these averages.
2. Estimation of the isoelectric level in each lead by searching for the flattest segment in the PQ interval.

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3. Determination of the ST level relative to the isoelectric level and the ST deviation function relative to the initial ST level in each lead, at a point 120 ms following the fiducial point (which for a monophasic QRS is usually placed by ARISTOTLE at the R wave peak).
4. Measurement of the initial ST level in each lead based on the average of the first 50 normal beats (learning phase) following ARISTOTLE's learning period.
5. Calculation of auxiliary functions (the R wave amplitudes, the angle of the mean electrical axis, and projections of the axis on both lead axes), and detection of axis shifts using information from ST deviation functions and auxiliary functions.
6. Continuous correction of the reference ST level (initially taken as zero) in each lead to account for axis shifts and slow drift of ST level, and calculation of the magnitude of ST deviation vector with regard to corrected reference ST level.
7. Detection of ischemic ST episodes, and determination of the onset, the end, and the location and amplitude of the extreme ST deviation of each episode, by application of the criteria defined in [3] to the calculated ST deviations.

2.1 Noise detection

Noise detection logic is needed to identify sudden baseline shifts, noise in the PQ and ST-T interval, and signal loss. Any of these may cause significant corruption of the average beat if not excluded, and may result in erroneous determination of the isoelectric or ST levels.

During the learning period the algorithm measures the peak-to-peak amplitude of each signal during a 440 ms window beginning 120 ms before ARISTOTLE's fiducial point, FP, for each beat. These measurements are averaged for each signal; at the end of the learning period, the parameter $PPMAX$ is set to the larger of the two averages.

During analysis, a beat is judged noisy if the peak-to-peak amplitude in either lead (defined over the same window as in the learning period) exceeds twice $PPMAX$. Possible baseline shift is identified if the ST level of the current beat, in either lead, measured at FP+120 ms, deviates by more than 400 μV from the average of the last twelve ST levels. Noise in the PQ segment ($FP - 120$ ms to $FP - 60$ ms) and the ST-T segment ($FP + 60$ ms to $FP + 320$ ms) is estimated by the sum of the absolute differences between consecutive samples within the given segment. The algorithm also measures $PPQRS$, the peak-to-peak amplitude over a 120 ms window centered on FP. If the noise estimate in the PQ segment exceeds half of $PPQRS$, or if the noise estimate in the ST-T segment exceeds three times $PPQRS$, the segment is considered noisy. Loss of a signal is identified whenever $PPQRS$ falls below 200 μV. (Since the algorithm is implemented as a post-processor to an arrhythmia detector, loss of all signals need not be dealt with at this level.)

2.2 Estimation of isoelectric level

The algorithm first searches backwards from FP for up to 30 ms for a sample at which the slope of the waveform equals zero or changes sign. If such a sample is not found within 30 ms of FP, searching ends at the last sample. The endpoint of the search may be the R peak, the Q peak, or end of the PQ segment, depending on the type of the QRS complex (monophasic or biphasic), and on the position of ARISTOTLE's fiducial point. From this point, the algorithm searches backwards sample-by-sample, for the flattest 16-ms segment within the previous 80 ms. For this purpose, the mean absolute deviation of each such segment from its own mean is determined, and the segment for which this value is minimum is judged the flattest. The mean amplitude of this segment is taken as an estimate of the isolectric level.

2.3 Detection of axis shifts

Position related changes in the electrical axis of the heart (axis shifts) may be characterized by sudden changes of parameters describing QRS morphology. Among the parameters in which axis shift can be recognized are the R wave amplitude, the angle of the mean electrical vector, and the projections of that vector onto the lead axes. During axis shift some or all of these parameters change rapidly (generally over a period of 30 seconds or less). At other times, including during ischemic ST episodes, these parameters are stable. Axis shifts are typically accompanied by step changes in ST level, while ischemic ST episodes exhibit less abrupt changes.

The algorithm determines ST levels relative to isoelectric levels for each average beat, and ST deviation levels ($st(i)$, where i denotes the lead number) relative to the initial ST level. ST levels are measured over a 20 ms window centered at $FP + 120$ ms (if the heart rate exceeds 120 bpm, the window is centered at $FP + 100$ ms).

For each average beat, several auxiliary functions are determined. The R wave amplitude in each lead, $r(i)$, is taken to be the maximum absolute deviation of the signal from the isoelectric level during the *PPQRS* window. The angle of the mean electrical vector, *an*, and its projections onto the lead axes, $p(i)$, are computed in the interval from $FP - 30$ ms to $FP + 30$ ms. Since the intervals from which average beats are composed differ in length, all these functions are resampled at a constant rate of 0.2 Hz (equidistant intervals of 5 sec) and smoothed with a seven-point moving average filter.

Axis shifts are identified by step changes in the resampled functions. Three operators are applied to each function:

1) an operator which estimates the mean absolute deviation over a *forward interval* of N samples, beginning $M/2 + 1$ samples after sample k:

$$f_A(k) = \frac{1}{N} \cdot \sum_{l=1}^{N} |f(k + M/2 + l) - a(k)| \, ;$$

2) a similar operator which estimates the mean absolute deviation over a *backward interval* of N samples, ending $M/2 + 1$ samples before sample k:

$$f_B(k) = \frac{1}{N} \cdot \sum_{l=1}^{N} |f(k - M/2 - l) - b(k)| \, ,$$

(where $f(k)$ is the function to which the given operator is applied, M is the separation in samples between the forward and the backward intervals, and $a(k)$ and $b(k)$ are the mean amplitudes of $f(k)$ over the forward interval and the backward interval, respectively.

3) an operator which estimates the amplitude of any step change in the function between the forward and backward intervals:

$$f_D(k) = |a(k) - b(k)| \, .$$

A step change is detected in a given function when the forward and backward intervals surrounding sample k are sufficiently flat (i.e., when $f_A(k)$ and $f_B(k)$ are both less than a predefined threshold, FT), and the amplitude of the step change, $f_D(k)$, exceeds another predefined threshold, DT. A non-ischemic ST change is identified when one of the combinations of step changes listed in table 1 is observed. For those rules which depend upon R wave amplitudes, $r(i, k)$, or projections of the mean electrical vector, $p(i, k)$, the step change amplitude is computed as the sum of the step change amplitudes for each lead or projection. The rules were determined empirically, from a study of trend plots of the functions.

$N\tau$	$M\tau$	*func*	FT	DT	*aux*	FT	DT
300	50	$st(i,k)$	5.4	100	–	–	–
150	75	$st(i,k)$	8.1	80	$r(i,k)$	22.5	300
150	75	$st(i,k)$	13.5	100	$r(i,k)$	90.0	900
150	75	$st(i,k)$	9.0	100	$p(i,k)$	90.0	400
150	75	$st(i,k)$	15.7	100	$an(k)$	9°	45°
150	75	$st(i,k)$	13.5	100	$r(i,k)$	45.0	600
					$p(i,k)$	90.0	400
90	75	$st(i,k)$	11.3	150	$r(i,k)$	75.0	700
					$p(i,k)$	75.0	500

Table 1: Summary of axis shift decision rules. Each row specifies the parameters of one decision rule. The parameters are: τ: sampling interval in seconds (for the computed functions); $N\tau$: length of forward and backward intervals in seconds; $M\tau$: separation between forward and backward intervals in seconds; *func* and *aux*: functions; FT: mean absolute deviation threshold; DT: step change amplitude threshold. Except as noted, the units of FT and DT are μV.

In the course of developing the algorithm we carefully examined the entire European ST-T Database. Particular care was given to distinguishing significant non-ischemic ST segment changes due to axis shifts from ischemic ST segment changes. Our study was supported by review of the original ECG charts, in which the characteristics of an axis shift are typically a sudden change in QRS shape, and stable ST segment levels before and after the shift. Regions where axis shifts occur are often accompanied by motion artifacts due to positional change. Nine non-ischemic ST episodes, accompanied by 16 significant axis shifts, are noted in the reference annotation files (some episodes are unterminated during the recordings). Our study indicates that there are another 9 non-ischemic ST episodes, accompanied by 12 axis shifts, which were not noted in the reference annotations.

2.4 Correction of the reference ST level

The reference ST level in each lead is continuously corrected sample-by-sample according to information obtained from the ST deviation function, the previous reference ST level, and decisions made by the algorithm with respect to the presence of ischemic or non-ischemic ST deviations. In general, the reference ST level tends to approach the ST deviation function, subject to constraints which depend on the ST deviation function and the reference ST level. The reference ST level for lead i at sample k, $st_r(i,k)$, is defined as the mean of the last L samples of the vector $stv(i,k)$, which describes recent variations of the ST deviation function and of the reference ST level:

$$st_r(i,k) = \frac{1}{L} \cdot \sum_{l=1}^{L} stv(i, k-l+1) ,$$

$$stv(i,k) = \begin{cases} st(i,k), & |st_r(i,k-1) - st(i,k)| \\ & \leq LT/2 \\ 0, & st_r(i,k-1) \leq 0 \ \wedge \\ & st(i,k) > \ LT \\ 0, & st_r(i,k-1) \geq 0 \ \wedge \\ & st(i,k) < -LT \\ st_r(i,k-1), & \text{otherwise} \end{cases}$$

where $L = 150$ (12.5 min), and $LT = 100\ \mu\text{V}$. The reference ST level approaches the ST deviation function if the absolute difference between them is no greater than 50 μV. If an ischemic episode is in progress, and the reference ST level and the ST deviation function have opposite signs, the reference ST level approaches its initial value. Otherwise, the reference ST level tends to remain the same. For the first five minutes after an ischemic ST episode is detected, the reference ST level may approach the ST deviation function slightly faster than at other times:

$$stv(i,k) = \begin{cases} st(i,k), & |st_r(i,k-1) - st(i,k)| \\ & < LT \\ st_r(i,k-1), & \text{otherwise} \end{cases}$$

During detected non-ischemic ST episodes, the reference ST level is set equal to the ST deviation function. At the end of the episode, the reference ST level and the vector $stv(i,k)$) are set to the average amplitude of $st(i)$ during the forward interval, as previously computed for detection of step changes.

3 Discussion and conclusions

The major advantage of our algorithm is its ability to detect axis shifts, and to correct the reference ST level for axis shifts or slow drift of ST level. A critical part of an ischemia detector is a well-constructed ST deviation function. Excluding noise-corrupted beats yielded a much "cleaner" ST deviation function than would be possible otherwise. By using ARISTOTLE's robustly determined fiducial point rather than the problematic PQ junction and J point for reference, we largely avoided introducing errors in ST level measurement due to fiducial misplacement, while maintaining excellent agreement with human measurements of extreme deviations. For a discussion of our algorithm's performance, see [4].

This paper presents our initial work on the problem of detection of axis shifts. Further improvements in the axis shift detection procedure and the axis shift decision rules seem possible. To obtain a more accurate ischemic ST change detector, our experience suggests that effort aimed towards improvements in reference ST level correction may be particularly rewarding.

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