Automatic Distinguishing Between Ischemic and Heart-Rate Related Transient ST Segment Episodes in Ambulatory ECG Records

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Abstract

In ambulatory ECG records, ischemia is manifested by transient ST segment episodes which may or may not be accompanied by increase in heart rate. There are also transient heart-rate related non-ischemic ST segment episodes present which are caused by change in heart rate. The goal of this work was to classify between these two types of ST episodes. The selected features to classify the ST episodes were changes of heart rate, changes of time domain morphologic parameters of the ST segment and changes of the Legendre orthonormal polynomial coefficients of the ST segment, all obtained on 20-second intervals at the beginning and at the extrema of each ST episode. The obtained sensitivity in classifying ischemic versus heart-rate related ST episodes using the LTST DB was 77.9%, while specificity was 73.9%.

1. Introduction

During ischemia, an imbalance occurs due to increased myocardial oxygen demand (demand ischemia, heart rate increase typically precedes ischemia), or due to decreased oxygen supply (supply ischemia, heart rate increase typically follows ischemia) what can lead to injury or death of heart tissue. Early markers of ischemia are transient ST segment deviation and transient ST segment morphology change, and can be detected in 24-hour ambulatory ECG records. There can also be transient non-ischemic ST segment morphology-change episodes which are not caused by an obstruction of the blood flow to the heart, but are caused by simultaneous change in heart rate. These transient non-ischemic heart-rate related ST segment episodes complicate automatic detection of true ischemia. The goal of this work was to automatically distinguish between transient ischemic and heart-rate related ST segment episodes.

2. Methods

2.1. The Long-Term ST Database

The Long-Term ST Database (LTST DB) [1] contains 86 2- or 3-lead 24-hour ambulatory ECG records, sampled at 250 samples s^{-1} per channel, and is intended for development and testing of automatic ischemia detectors. The records were collected during routine clinical practice to model significant number of real-world clinical conditions. During development of the LTST DB, a considerable preprocessing phase took place in order to derive a number of time series of diagnostic and morphologic parameters. The preprocessing phase included: ARISTOTLE's [2] analysis yielding stable QRS complex fiducial points (FP), removal of noise, derivation of the instantaneous heart rate, automatic search for the isoelectric level, measurement of the ST segment level, derivation of the Karhunen-Loève Transform (KLT) based ST segment and QRS complex morphology feature vectors, removal of abnormal beats and their neighbors, and removal of noisy beats. Then the positions of the isoelectric level and J point were set manually by human expert annotators using time averaged heart beats computed over 16-second intervals surrounding each normal and non-noisy heart beat which passed the preprocessing phase. These positions were then used to derive the ST segment level functions, $stlev(i, j)$, where i denotes the lead number, and j denotes the heart beat number. The $stlev(i, j)$ were obtained by measuring the ST segment level at the point J+80ms (or 60 ms if heart rate exceeded 120 bpm). The $stlev(i, j)$ (and all the time series obtained during the preprocessing phase) were then resampled and smoothed at a equidistant time step of $\Delta T = 2$s. The ST segment deviation functions, $stdev(i, k)$, where k now denotes the sample number in the time series, were obtained by subtracting the time varying ST segment reference level, $stref(i, k)$, from the $stlev(i, j)$. The $stref(i, k)$ were obtained by manual setting of the local reference annotations throughout the records. Transient ischemic and heart-rate related ST segment episodes were then manually annotated in each ECG lead by human expert annotators in the ST segment deviation functions, $stdev(i, k)$.

Human expert annotators of the LTST DB established a gold standard where transient ischemic and heart-rate related ST segment episodes were annotated with regard to changes in the heart rate and ST segment morphology, and with regard to accompanied clinical re-

ports. Ischemic ST segment morphology-change class included: horizontal flattening, down sloping, scooping, or depression/elevation; while heart-rate related ST segment morphology-change class included: J point depression with positive slope, moving of T wave into ST segment, T wave peaking, or parallel shift of ST segment level. To be annotated, a transient ST segment episode had to be significant, satisfying the following criteria (according to the annotation protocol B of the LTST DB, refer also to figure 1). An episode begins when the magnitude of the ST segment deviation function first exceeds 50μV; then the deviation must reach a magnitude of 100μV or more throughout a continuous interval of at least 30 s; and finally the episode ends when the deviation becomes lower than 50μV, provided that it does not exceed 50μV in the following 30s. According to the annotation protocol B, the LTST DB contains 1130 ischemic and 234 heart-rate related ST segment episodes.

2.2. The selected features

In order to classify between ischemic and heart-rate related ST segment episodes we chose several ECG diagnostic and morphologic parameters: heart rate values, the Mahanalobis distance of the first five KLT coefficients of the QRS complex, time domain parameters of the ST segment morphology, and the Legendre orthonormal polynomial coefficients of the ST segment morphology and the Euclidean distance of the first three coefficients. To estimate how the values of diagnostic and morphologic parameters change during transient ST segment episodes, we first calculated means of parameter values for each of the parameter, in their time series, on three 20-second intervals (see figure 1), similarly as in [3], located before the beginning (interval I_1), right after the beginning (I_2) and around the extrema (I_3) for each ST segment episode. We then calculated features, F, for each of the parameter, P, and for each ST episode, as the differences of the mean parameter values in the intervals I_1, I_2, and I_3, following:

$$F_{l1} = |\overline{P_l} - \overline{P_1}|, \quad l = 2, 3. \tag{1}$$

The selected heart rate features (group HR) estimating the heart rate changes along the ST episodes were HR_{21} and HR_{31} in the intervals I_1, I_2 and I_3; and $\overline{HR_3}$ ($HR_{\max}$) in the interval I_3 estimating heart rate at the extrema of the ST episodes. (The time series of heart rate, $HR(k)$, where k denotes the sample number, are stored in the *raw.dmy files of the LTST DB.)

Regarding the Mahanalobis distance of the first five KLT coefficients of the QRS complex (group MD), we choose MD_{31} as a feature estimating the QRS complex morphology change along the ST episodes in the intervals I_1 and I_3. (The time series of the KLT coefficients and of the Mahanalobis distance, $MD(k)$, are stored in the *.klt and *raw.dmy files of the LTST DB.)

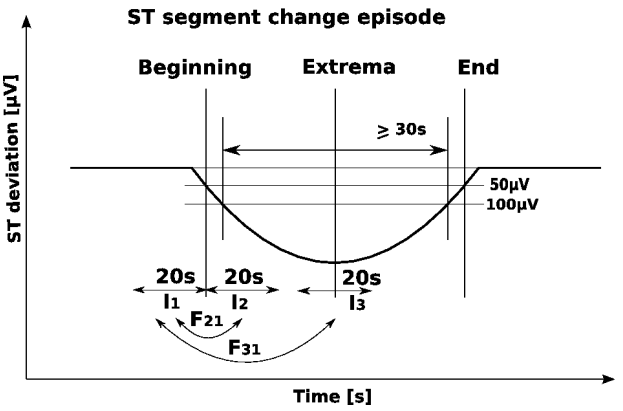

Figure 1. Intervals used to calculate the features, F, for each of the parameter, P, and for each ST episode, as the differences of the mean parameter values from the intervals at the beginning and extrema of ST episodes.

The selected time domain features of the ST segment morphology (group ST) estimating the ST segment morphology changes along the ST episodes were the ST segment deviation change, ST_{31}, in the intervals I_1 and I_3, and the ST segment slope change, SL_{21} and SL_{31}, in the intervals I_1, I_2 and I_3. The ST segment deviation was measured at the point J+80ms (or 60ms if heart rate exceeds 120 bpm), while the ST segment slope was measured as the difference between the amplitudes of the ST segment level at the point J+80ms(60 ms) and at the point J+20ms. (The time series of the ST segment deviation, $ST(i,k)$, where i denotes the lead number and k the sample number, are stored in the *.stf and *raw.dmy files; while the values of the ST segment level, $stlev(i,j)$, where j denotes the heart beat number, obtained on the average heart beats composed from normal and non-noisy heart beats in the 16-second windows, are stored in the *.16a files of the LTST DB.) Another selected time domain feature of the ST segment morphology changes was the root mean square based value of the ST segment shape change in the intervals I_1 and I_3, denoted RMS_{31}. Initially, the mean values of the ST segment level at the selected points: J, J+20ms, J+40ms, J+60ms, J+80ms, J+100ms, J+120ms, were calculated for averaged heart beats (composed from normal and non-noisy heart beats in the 16-second windows) in the intervals I_1 and I_3. Next, the squares of the differences of the mean values of the ST segment level at these selected points between the intervals I_1 and I_3 were computed. Finally, the square root of the sum of the squared differences was computed. (The values of the ST segment levels at these selected points are stored in the *.16a files of the LTST DB.)

The selected Legendre orthonormal polynomial coeffi-

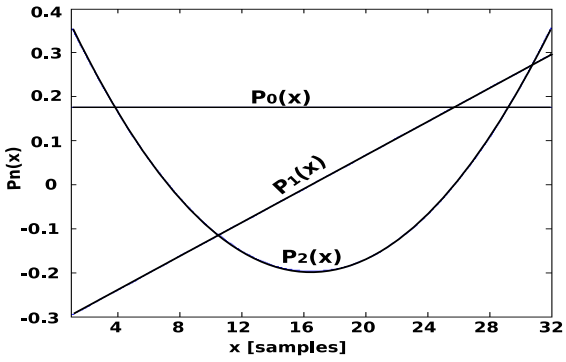

Figure 2. The first three Legendre orthonormal basis functions after the Gram-Schmidt orthonormalization (x axis - the sample number, 32 samples, length 128ms).

cients features of the ST segment morphology (group LPC) estimating the ST segment morphology change along the ST episodes were the change of the first three coefficients, $L1_{31}$, $L2_{31}$ and $L3_{31}$, and the change of the Euclidean distance of the first three Legendre coefficients, LE_{31}, in the intervals I_1 and I_3. The first three Legendre polynomials are following:

$$P_0(x) = 1, \quad P_1(x) = x, \quad P_2(x) = \frac{1}{2}(3x^2 - 1). \quad (2)$$

They are orthogonal over the interval [-1,+1]. We selected the Legendre polynomials because of their orthogonality, and because the first three polynomials best fit typical shapes of the ST segment morphology thus allowing direct insight into the ST segment morphology changes through the feature space. The first three Legendre orthogonal polynomials (basis functions): constant, linear and square function, are very similar to typical ST segment morphology changes: level, slope and scooping, during transient ST segment episodes. Figure 2 shows the first three Legendre orthonormal basis functions after the Gram-Schmidt orthonormalization. The basis functions were applied to each individual normal and non-noisy heart beat of the LTST DB of the records, in each ECG lead, in the window from the FP+40ms to FP+168ms. The time series of the coefficients thus obtained were then resampled and smoothed. (The time series of the Legendre orthonormal polynomial coefficients, $Ln(i,j)$ and $Ln(i,k)$, and of the Euclidean distance, $LE(i,k)$, will be added to the LTST DB, and will be freely available until December 2008.)

3. Results

The mean values and the standard deviations of the selected features for all transient ischemic and all heart-rate related transient ST segment episodes of the LTST DB are shown in table 1. We selected the features after evaluating their separability of both types of ST episodes using the ANOVA. The lower the p-value of the ANOVA, the higher the separability. Table 1 also shows the performance in classification when each of the selected features is used individually. The selected features to classify ST segment episodes, when used individually, show high sensitivity, Se, and low specificity, Sp, in distinguishing ischemic from heart-rate related episodes, and lower mean values of the features for ischemic episodes (HR_{21}, HR_{31}, SL_{21}, SL_{31}, $L2_{31}$, $L3_{31}$), or, they show low Se and high Sp, and lower mean values of the features for heart-rate related episodes (MD_{31}, ST_{31}, RMS_{31}, $L1_{31}$, LE_{31}). This result indicates that during ischemic episodes, in the average, there is less significant change in the heart rate and ST segment slope, while during heart-rate related episodes, which are always accompanied by change in heart rate, there is less significant change in the QRS complex shape, ST segment level and ST segment morphology. The maximal heart rate, $HR_{\max}$, is in the average higher during heart-rate related episodes and shows higer Sp. Some of the selected features when used individually for the classification of ST episodes (HR_{21}, HR_{31}, $HR_{\max}$, MD_{31}, SL_{21}, $L1_{31}$, LE_{31}) show low p-value of the ANOVA and still do not have high classification performance, but are good complement to other features when used jointly for the classification. The best single feature for the classification from the group HR is $HR_{\max}$. The best single feature from the group ST is the ST segment slope change, SL_{21}, and from the group LPC, the Euclidean distance of the first three Legendre coefficients, LE_{31}. The heart rate features (group HR) and time domain ST segment morphology features (group ST), see table 2, show higher Se, while the Legendre basis functions features (group LPC)

	Ischemic		Heart-rate		ANOVA	Performance	
Feature	mean	st.d.	mean	st.d.	p-value	Se	Sp
HR_{21}	4.5	6.0	8.6	7.4	0	79.4	48.3
HR_{31}	11.6	11.6	21.7	13.7	0	75.5	55.6
$HR_{\max}$	90.4	23.9	111.0	21.7	0	67.3	71.4
MD_{31}	224.6	200.8	143.5	169.1	$4.7 \cdot 10^{-8}$	44.0	72.2
ST_{31}	182.7	115.4	150.9	102.2	$9.9 \cdot 10^{-5}$	42.3	73.1
SL_{21}	18.3	18.0	33.7	25.1	0	77.0	53.0
SL_{31}	53.0	52.4	59.5	39.0	$7.0 \cdot 10^{-2}$	67.1	49.6
RMS_{31}	482.9	312.2	388.5	161.8	$7.8 \cdot 10^{-6}$	43.5	68.4
$L1_{31}$	182.1	127.0	133.7	62.3	$1.4 \cdot 10^{-8}$	45.8	71.4
$L2_{31}$	30.5	30.6	34.0	29.0	$1.2 \cdot 10^{-1}$	66.9	45.3
$L3_{31}$	10.3	13.5	11.5	10.2	$1.7 \cdot 10^{-1}$	70.2	41.9
LE_{31}	158.1	123.0	105.5	61.7	$2.6 \cdot 10^{-10}$	47.4	70.9

Table 1. List of the selected features sorted by groups, their means and standard deviations for ischemic and heart-rate related ST episodes of the LTST DB annotated according to the annotation protocol B of the LTST DB, p-value of the ANOVA, and sensitivity, Se, and specificity, Sp, in classifying of the ST segment episodes, when each feature is used individually for the classification. The highest performances per group are boxed.

Groups	Features	Se	Sp
HR	HR_{21}, HR_{31}, $HR_{\max}$	77.0	65.8
HR, MD	HR_{21}, HR_{31}, $HR_{\max}$ | MD_{31}	76.6	67.1
ST	ST_{31}, SL_{21}, SL_{31}, RMS_{31}	76.4	58.2
ST, MD	ST_{31}, SL_{21}, SL_{31}, RMS_{31} | MD_{31}	74.3	64.5
LPC	$L1_{31}$, $L2_{31}$, $L3_{31}$, LE_{31}	49.7	75.6
LPC, MD	$L1_{31}$, $L2_{31}$, $L3_{31}$, LE_{31} | MD_{31}	46.6	76.5
HR, ST	HR_{21}, HR_{31}, $HR_{\max}$ | ST_{31}, SL_{21}, SL_{31}, RMS_{31}	79.6	70.1
HR, ST, MD	HR_{21}, HR_{31}, $HR_{\max}$ | ST_{31}, SL_{21}, SL_{31}, RMS_{31} | MD_{31}	79.3	71.4
HR, LPC	HR_{21}, HR_{31}, $HR_{\max}$ | $L1_{31}$, $L2_{31}$, $L3_{31}$, LE_{31}	77.3	71.8
HR, LPC, MD	HR_{21}, HR_{31}, $HR_{\max}$ | $L1_{31}$, $L2_{31}$, $L3_{31}$, LE_{31} | MD_{31}	75.9	73.5
HR, ST, LPC	HR_{21}, HR_{31}, $HR_{\max}$ | ST_{31}, SL_{21}, SL_{31}, RMS_{31} | $L1_{31}$, $L2_{31}$, $L3_{31}$, LE_{31}	78.2	72.2
HR, ST, LPC, MD	HR_{21}, HR_{31}, $HR_{\max}$ | ST_{31}, SL_{21}, SL_{31}, RMS_{31} | $L1_{31}$, $L2_{31}$, $L3_{31}$, LE_{31} | MD_{31}	77.9	73.9

Table 2. Sensitivity, Se, and specificity, Sp, in classifying ischemic and heart-rate related ST segment episodes annotated according to annotation protocol B of the LTST DB when groups of the selected features are used. The highest performances per selected groups are boxed.

show higher Sp. The obtained performance is approximately equal if using jointly groups HR and ST, or groups HR and LPC, and is the best if using all the features, with the Se of 77.9% and Sp of 73.9%.

4. Discussion and conclusions

The heart rate features (group HR) are the most significant features to classify the episodes. The maximal heart rate, $HR_{\max}$, is higher in heart-rate related episodes. In heart-rate related episodes there is higher change in heart rate at the beginning, HR_{21}, and at the extrema of the episodes, HR_{31}, then in ischemic episodes. Both features have higher Se then Sp. This is expected. In heart-rate related episodes the change in heart rate occurs simultaneously at the beginning of the episodes (and is always present), mostly the increase; while in ischemic episodes the heart rate increases prior to the beginning of the episodes in demand ischemia, or increases after the beginning in supply ischemia, or the increase in heart rate may not be significant (nor sometimes even present) in supply ischemia. The change in the Mahanalobis distances of the QRS complex KLT coefficients, MD_{31}, is higher in ischemic episodes. In ischemic episodes QRS complex morphology change usually occurs due to simultaneous shift of the mean QRS complex electrical axis.

The ST segment deviation change, ST_{31}, is higher in ischemic episodes. The ST segment slope change, SL_{21}, is higher in heart-rate related episodes, while the ST slope change, SL_{31}, is similar in both types of episodes. This means that in heart-rate related episodes the ST segment slope changes a lot already at the beginning of the episodes. This may be due to the most often simultaneous move of the T wave closer to the QRS complex already at the beginning of heart rate related ST episodes. The time domain feature estimating the change of ST segment morphology, RMS_{31}, is higher in ischemic episodes. This means that the ST segment shape changes more in ischemic episodes.

The change of the first Legendre coefficient, $L1_{31}$, represents the change of the ST segment deviation (similar to the time domain ST segment deviation change, ST_{31}) and is higher in ischemic episodes as well. The change of the second coefficient, $L2_{31}$, represents the change of the ST segment slope (as the time domain ST segment slope change, SL_{31}) and is similar in both types of episodes as well. The change of the third coefficient, $L3_{31}$, represents the scooping of the ST segment and is not significant. This is expected since the scooping is not very common. The change in the Euclidean distance of the first three Legendre coefficients, LE_{31}, represents the overall ST segment morphology change and is higher in ischemic episodes, similarly as the time domain feature estimating the overall change of ST segment morphology, RMS_{31}.

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