Characterization of Transient Ischemic and Non-ischemic ST Segment Changes

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Abstract

Using trend plots of heart rate, Karhunen-Loève coefficient representations of ST segments and QRS complexes, and time-domain measures of ST level and QRS morphology, we have studied temporal patterns of ST change episodes and their associations with heart rate changes and arrhythmias in the European Society of Cardiology ST-T Database. We describe methods for discriminating between ischemic and non-ischemic ST episodes, and for interpreting mixed ischemic and non-ischemic ST changes as well as long-term drift of ST level. Further, we describe distinctly different temporal patterns in ischemic ST episodes, and the association of heart rate changes and arrhythmias with ischemic ST episodes.

1. Introduction

Ambulatory ECG monitoring (AEM) is widely used for the analysis of transient symptomatic and silent ST-segment changes suggesting myocardial ischemia. ST changes may be observed in a variety of contexts other than ischemia, including ventricular hypertrophy, hyperventilation, electrolyte abnormalities, response to medication, mitral valve prolapse, pulmonary embolism, pericarditis, and response to temperature changes. Reliable ST analyzers must distinguish these *non-ischemic ST changes* from the clinically significant *ischemic ST changes.* The most troublesome of these non-ischemic ST changes are position-related (postural) changes in the electrical axis of the heart, which may cause sudden and significant (>100 μV) shifts of ST level; and very slow but significant (>100 μV) drift of ST level provoked by effects of medication on repolarization, slow (non-postural) changes in the cardiac electrical axis, or the effects of changes in heart rate on repolarization. Such changes complicate both automated and manual detection of true ischemic ST episodes.

Since physiologic signals other than the ECG are usually not available during AEM, features of the ECG must be used to distinguish these non-ischemic events from others likely to be associated with ischemia. By assessing the temporal course of ST deviation levels together with supplementary criteria (based on observation of sudden changes in ST deviation level, identical orientation of PQ and ST segments, and simultaneous change in R and P wave amplitudes), Völler *et al.* obtained improved detection of transient ischemia, while avoiding detection of non-ischemic ST changes [1]. Progress in this area has been hampered by a lack of generally accepted ECG criteria for classifying ST changes as ischemic or non-ischemic. Indeed, the ECG provides only indirect evidence of ischemia. Although it is not possible to state with certainty that *any* ST change is ischemic, based on the ECG alone, it is possible to state in many cases that an ST change is definitely non-ischemic.

Standard visual analysis of the ECG waveform does not readily permit assessment of the features that allow one to distinguish ischemic from non-ischemic ST changes, or to distinguish among different types of ischemic ST changes. Careful study of AEM recordings, with attention to medium- and long-term trends (on the order of minutes to hours) can shed light on the mechanisms that generate ischemic ST changes. The aim of this paper is to characterize and quantify differences in the behavior of transient ischemic and non-ischemic ST changes, to characterize temporal patterns of ischemic ST episodes, and to examine their association with changes in cardiac rate and ectopy.

2. Methods

For this study, we preprocessed the recordings in the European Society of Cardiology (ESC) ST-T Database [2] to obtain trend plots of several *time-domain metrics* and of *Karhunen-Loève (KL) coefficient representations* of the ST-segment and QRS-complex data. Visualizing features in trend plot form permits displaying the information globally and in a manner superior to visual examination of raw signals. The Karhunen-Loève Transform (KLT) representation of wave shape is robust, offers high representational power, and provides reliable and efficient detection of noisy beats. We chose the KL representation of the QRS in order to track changes in QRS morphology, which are the most sensitive indicators of axis shifts associated with non-ischemic ST changes. We chose the KL representation of the ST segment to track changes in ST morphology, in order to have the best opportunity of observing ST changes that might not be apparent on the basis of standard differential (level or slope) measurements. Finally, we included the traditional time-domain measures to permit quantitative measurement of ST changes in conventional terms.

2.1. Applying the KLT

To derive the KLT basis functions, we used all 90 records of the ESC Database. Abnormal beats (classified by the ARISTOTLE arrhythmia detector [3]), their neighbors and noisy beats (detected by the time-domain algorithms [4]) were discarded. The remaining 744,800 heartbeats were corrected to the isoelectric level [4] and used to derive robust estimates of the covariance matrices of the QRS and ST pattern vectors with outliers excluded, using methods we have described previously [5]. The components of the pattern vectors are 16 baseline-corrected samples at 8 ms intervals from each of the two ECG signals. The QRS pattern vectors begin 96 ms before ARISTOTLE's fiducial point (FP), and the ST segment pattern vectors begin 40 ms after FP. The KLT basis functions are the eigenvectors of the covariance matrices, ordered by their associated eigenvalues arranged in descending order.

The first five QRS coefficients account for 93% of the QRS energy, and the first five ST coefficients account for 97% of the ST energy. We found that this number of coefficients affords the greatest separation in terms of residual energy between waveforms identified as noisy and those identified as clean by the expert annotators of the ESC Database.

2.2. Visualization of the features

The signals were initially preprocessed using the ARISTOTLE arrhythmia detector, low-lass filtered using a 6-pole Butterworth filter (cut-off frequency of 55Hz) and baseline corrected using the cubic spline technique. Ectopic beats and their neighbors were rejected. Both sets of KL basis functions were applied to each remaining heartbeat, and noisy beats were detected in the KL space. A heartbeat was considered noisy if the normalized residual error for the ST segment or for the QRS complex exceeded 25% ($N = 5$), or if the ST or QRS feature vector differed sufficiently (by more than $m+\sigma = 8.16$; m and σ are the expected mean and standard deviation of a chi-squared random variable with $N = 5$ degrees of freedom) from the mean ST or QRS feature vector of the last 15 heartbeats. All the features of the remaining heartbeats were smoothed (using a 15 point moving average), resampled at uniform intervals of 2 sec, and additionally smoothed using a 9 point moving average. Figure 1 illustrates the trend plots obtained in this way.

W	$\overline{HR}_I$ / $\overline{HR}_B$				
	1.05	1.10	1.15	0.95	
1 *min*	36	22	9	14	[%]
3 *min*	42	28	16	9	[%]
5 *min*	48	33	20	9	[%]

Table 1. Percent of ischemic episodes for which the change in the mean heart rate during the episodes as compared to before the episodes was found to be $\geq$5%, $\geq$10%, $\geq$15%, and $\leq$-5%. ($\overline{HR}_I$ - mean heart rate during the episodes; $\overline{HR}_B$, - mean heart rate in the window W immediately before the episodes.)

3. Results

The 90 2-hour records of the Database contained 259 distinct ST episodes, of which 250 are annotated as ischemic and 9 as non-ischemic. The ischemic ST episodes of the Database generally show a triangular (see Figures 1 and 2) and quite repeatable temporal structure. As illustrated in Figure 2, episodes may appear ***sporadically***, as isolated episodes or without discernable patterns of repetition (in 66 records); ***repetitively***, as quasi-periodic episodes occurring throughout the record (in 13 records); or in ***salvos***, quasi-periodic episodes generally at a more rapid rate than in the previous group, occurring during only a portion of the record (in 7 records). Episodes of ST depression are more frequent, and may last up to an hour or more, as compared to episodes of elevation, which last no more than 20 minutes in the Database. The extrema of the ST deviation level appear normally distributed, and depressions of -100 μV are the most frequent. We examined the coincidence of heart rate changes and arrhythmias (abnormal beats identified by ARISTOTLE) with ischemic ST episodes. Table 1 shows that in 48% of episodes there are increases in heart rate of at least 5% as compared to heart rates immediately before the episodes. Furthermore, data suggest that heart rate is accelerating immediately prior to the ischemic episo-

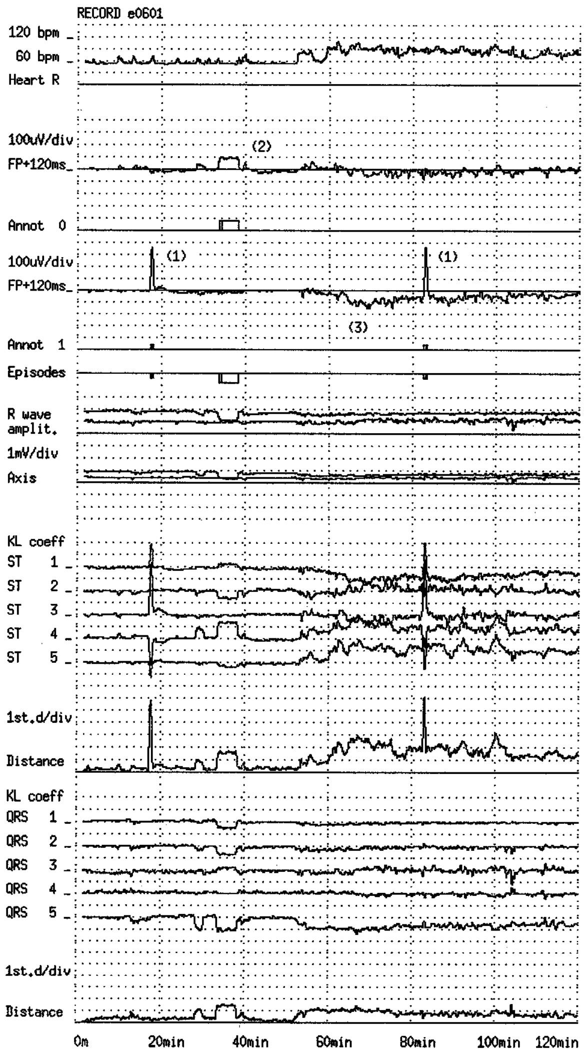

Figure 1. Trend plots of record e0601 of the Database. Record contains two ischemic episodes (1), one non-ischemic episode (2), and significant slow drift (3). From top to bottom: heart rate, ST segment deviation levels for both leads at 120ms after the ARISTOTLE's fiducial point (resolution: 100 μV) with the corresponding reference ST episode annotation streams; combined reference ST annotation stream in the sense of logical OR function; R wave amplitudes and projections of the mean electrical axis to both lead axes (resolution: 1 mV); and time-series of the first 5 KL coefficient representation of ST segments and QRS complexes (resolution: 1 st.dev. - eigenvalue: λ_i) with corresponding Mahalanobis distance measure (normalized Euclidean distance) when using the first 5 KL coefficients (resolution: 1 st.dev.)

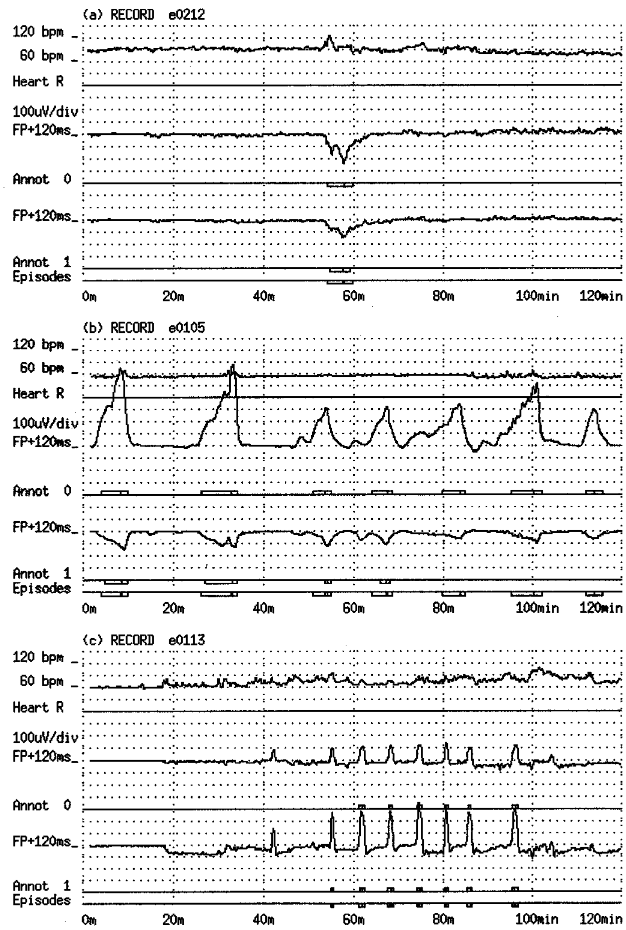

Figure 2. Abbreviated trend plots of three records (e0212, e0105,and e0113) from the Database. Only heart rate, ST segment deviation and corresponding ST annotations for two leads are shown. Three types of ST segment episode temporal structure are illustrated: sporadic (a), repetitive (b), and salvo (c). (Note that some episodes in the salvo were not annotated, but are obvious in the trend plot.)

des. (See an example in Figure 2a.) Nine percent of episodes showed a drop in heart rate. The remaining 43% of episodes were associated with little or no change in heart rate. Abnormal beats were found to be 1.9 times more frequent during ischemic ST episodes than elsewhere in the records.

A sudden change in the electrical axis of the heart (axis shift) is an event that typically takes 30 sec or more, up to 2 minutes. It is characterized by a change in QRS complex morphology and is often accompanied by motion artifacts resulting from positional change.

Axis shift *may* consequently cause sudden significant (>100 μV) change of ST level. Since the mean electrical axis tends to return to its usual direction, another axis shift often follows. The mean electrical axis may also slowly move out of *or* into its usual direction. Such an axis shift interval, if associated with a significant (>100 μV) concurrent change of ST level, is a non-ischemic ST episode. These episodes are thus characterized by a significant axis shift at the beginning *and/or* end of the episode. The time course of ST level typically is rectangular in shape (see Figure 1), with a maximum deviation <300 μV.

In addition to the nine annotated non-ischemic episodes (which contain 16 significant axis shifts) in the Database, there are another seven episodes (with 11 axis shifts) with ST changes of almost 100 μV (11 axis shifts) which were below annotation threshold. Three of these are *mixed* (i.e., non-ischemic episodes containing ischemic episodes within; these were found in records e0106, e0122 and e0603). Moreover, we found another eight non-ischemic episodes (3 mixed, 14 axis shifts) with maximum deviations between 50 and 100 μV.

Significant (>100 μV) slow drift of ST deviation level (see Figure 1) was found in 17 records (18.9%). Of these, 15 records contain also ischemic episodes. Slow drift is accompanied by increases in heart rate in eight of the 17 records, suggesting rate-related ST-T changes likely to be non-ischemic. Visual examination also showed lesser degrees (50-100 μV) of slow drift in another 20 records (with accompanying increases in heart rate in four of these records).

4. Discussion and conclusions

The ESC Database contains a wealth of ECG data obtained during transient ischemic and non-ischemic ST-T changes. We have developed a method to represent the important features of the data, and to permit efficient visual examination of the Database. We used these multi-parameter trend plots to characterize the temporal patterns of ischemic ST episodes; to characterize and quantify differences in the temporal behavior of ischemic and non-ischemic ST changes; to determine the relative incidence of non-ischemic ST changes in the Database; and to examine the relationship between arrhythmias, heart rate increases, and ischemic ST changes. The study also provides valuable intuitive insights to the data, which are helpful in the design of automated ST-T segment analysis algorithms, particularly with respect to detection of slow baseline shifts and non-ischemic ST changes.

The number of ischemic episodes per record of the Database is small. One record contains 13 episodes, five records contain seven episodes each, and three records contain six episodes each; none of the other records contain more than five episodes each. Records of longer duration would be helpful in more fully exploring the temporal structure of ischemic episodes.

Non-ischemic episodes (9 + 7; 6.2%) and mixed episodes (3; 1.2%) are rare in the ESC Database. To better establish detection criteria for these episodes, and to evaluate detectors that implement these criteria, may also require additional recordings. Ischemic episodes occur in repetitive or salvo-type patterns in 20 of the 90 records (22%), and sporadically in 66 records (73%). Based on the observed associations between these patterns and changes in cardiac rate and ectopy, we suggest that differing temporal patterns of ST change reflect differing physiologic mechanisms responsible for ischemia, which may in turn require differing therapeutic interventions.

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