Robust Measure of ST/HR Hysteresis in Stress Test ECG Recordings

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Abstract

In stress test ECG analysis, the so-called ST/HR hysteresis has recently been suggested to improve coronary artery disease (CAD) diagnosis. This parameter is estimated from the ST versus HR diagram including exercise and recovery phases. Unluckily, ST measurements are adversely affected by noise during the test. In this study we propose a method to automatically estimate the ST/HR hysteresis, incorporating multiple stage noise attenuation. The method is based on averaging and rejection of noisy beats. Evaluation is done on simulated exercise test recordings, constructed from real ECG averaged beats adding actual noise from stress test records. Results on a total of 216 different records, with RMS noise levels ranging from 114 to 979 μV, give a reduction in estimation error in the ST/HR diagram of 77.98% (from 168 to 37 μV) in mean and of 76.38% (from 271 to 63 μV) in standard deviation. This method may be considered as a suitable and robust tool for reliable ST/HR hysteresis estimation.

1. Introduction

One of the major cardiac disfunctions is coronary artery disease (CAD). Stress test is a very common, non-invasive and widely accessible method for diagnosing CAD. However it suffers from lack of good compromise between sensitivity and specificity. Imaging techniques are better suited for diagnosis, but with a higher cost, both economical and procedural. Then, alternatives to improve the performance of the ECG analysis from stress test are still challenging. Among them, clinical indexes based on the ST depression versus HR (ST/HR) diagram have been suggested [1]. The so-called ST/HR hysteresis, which integrates ST/HR diagram during both exercise and recovery phases of the test, was found to be the most accurate diagnostic variable [2]. This parameter is defined as the average difference in ST depression between the exercise and recovery phases measured at the same values of HR, for up to 3 minutes of the recovery phase. To estimate the ST/HR hysteresis both ST depression and HR must be measured on the ECG. However, the high noise content in exercise test recordings (mainly due to muscular activity) and its non-stationary characteristics lead to unreliable measures. Thus, techniques to alleviate this problem should be explored before evaluation of its clinical impact on CAD diagnosis. In this study we propose a method to automatically estimate the ST/HR hysteresis in the presence of stress test noise.

2. Methods

The method developed to give a robust ST/HR index is divided into three stages: first, a *preprocessing* step where filtering and beat rejection are applied to the raw ECG signal prior to a weighted averaging; then, the *postprocessing* step identifies and discards potentially noisy average beats based on their noise variance; finally, in the *measurement* step, the ST/HR hysteresis loop is generated from the averaged beat series.

2.1. Preprocessing

Some signal processing techniques were applied to the ECGs in order to reduce the effect of noise: QRS detection and selection of *normal beats* [3]; baseline wander attenuation using *cubic splines* interpolation (isoelectric level knots estimated averaging 20 ms of signal starting 80 ms before QRS mark); and rejection of beats presenting difference in their mean isoelectric level with respect to adjacent beats of more than 600 μV.

Due to the highly non-stationary characteristics of exercise test noise, a running weighted averaging was applied to the signal. Each beat was multiplied by a coefficient inversely proportional to its noise variance [4]. This noise variance was estimated as the signal power after high-pass filtering (cut-off frequency 15 Hz) in the interval ($QRS - 150$ ms, $QRS + 0.7RR$ ms), where QRS represents the QRS mark and RR is the distance between 2 consecutive beats (in ms). A running weighted average of 10 beats was performed, sliding 5 beats each time so that each 5 beat period an average beat and its corresponding ensemble variance (estimation of the ensemble noise), were obtained and stored for later use.

2.2. Postprocessing

Despite the first stage and owing to the high noise content in exercise test recordings, unreliable ST measures may often occur. Therefore, it is necessary to exclude noisy data before ST/HR hysteresis computation. Those average beats presenting too high noise variance, (called *outliers*), were rejected. Since the noise level is not constant from the beginning of the test to the stress peak, the rejection threshold should be variant according to the different stages of the test. To this end, we used an adaptive threshold rejection method based on the *median absolute deviation* (MAD) of the averaged beat noise variance [5]. Beats whose noise variance differed from its median more than its assigned threshold were discarded (see Fig. 1). The threshold associated to each average beat was defined as the median value (estimated in an interval of 2 minutes) plus its respective median absolute deviation (called MAD), estimated in an interval of 5 minutes.

Due to the high noise level at stress peak and its non-stationary characteristics, all average beats surrounding the peak may be considered as *outliers* and, therefore, discarded. If all beats in an interval of 15 seconds before and after stress peak were rejected, the average beat presenting the minimum noise variance in that interval was kept to avoid loosing all data at stress peak.

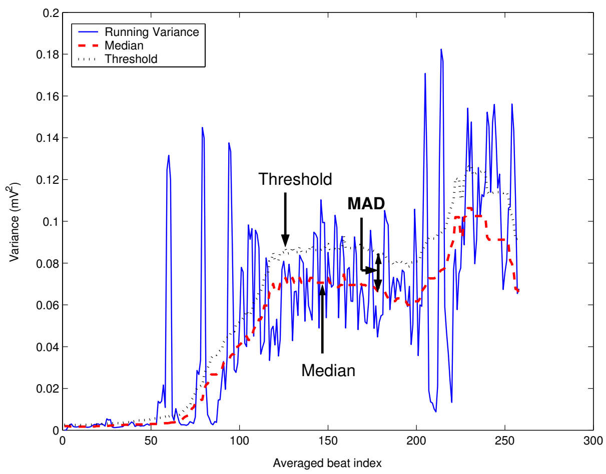

Figure 1. Example of beat rejection based on MAD. Beats with noise variance higher than its threshold are rejected.

2.3. Measurement

ST measurement was performed on each of the non-rejected weighted-averaged beats. ST segment level was estimated averaging 10 ms of signal at a HR-dependent distance from the QRS fiducial point, according to [6]:

$$STpoint = QRSpoint + (40ms + 1.2 \cdot RR^{1/2}).$$

The QRS fiducial point was defined as the center of gravity of the whole QRS complex. The RR value assigned to each of the averaged beats was computed as the median of the RR values of the 10 original beats included in its average. The isoelectric level was obtained averaging 10 ms of the PR interval starting 70 ms before the QRS fiducial point.

Then, the ST/HR diagram was constructed: a unique ST depression value was obtained for each HR value (mean of all ST values corresponding to the same HR, differentiating between exercise and recovery phases) and a median filtering of 9 samples was applied to the ST trend.

The ST/HR hysteresis was computed from this ST/HR diagram, integrating the difference between ST depression during exercise and recovery over the HR from the first 3 minutes of the recovery value to the maximum HR (stress peak). The integrated net difference was divided by the integration interval HR difference [2]. See Fig. 2.

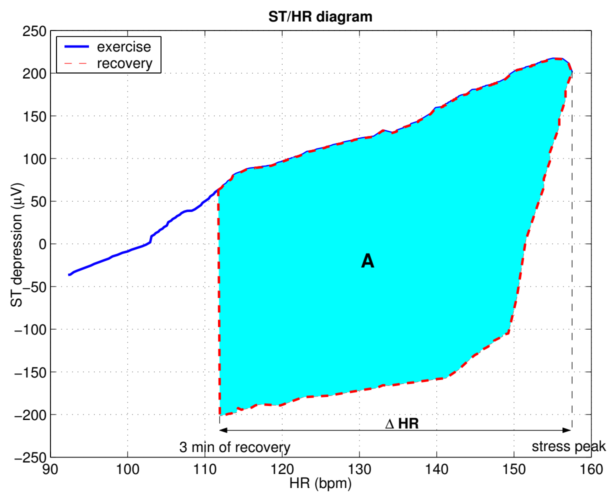

Figure 2. ST/HR diagram. ST/HR hysteresis = $\frac{A}{\Delta HR}$; A = area between the recovery and exercise ST depression values; ΔHR = HR difference between stress peak and the first 3 minutes of recovery.

To establish the limit of the first 3 minutes of the recovery, the stress peak needs to be estimated. Since at this point the signal is especially noisy, a moving-average filter of 5 beats was applied to the HR trend; then, the maximum HR was identified as the stress peak.

3. Simulation set up

Evaluation of the method is difficult, since no reference can be obtained in actual ECG records. Thus, an ECG record was constructed from a set of 15 weighted average

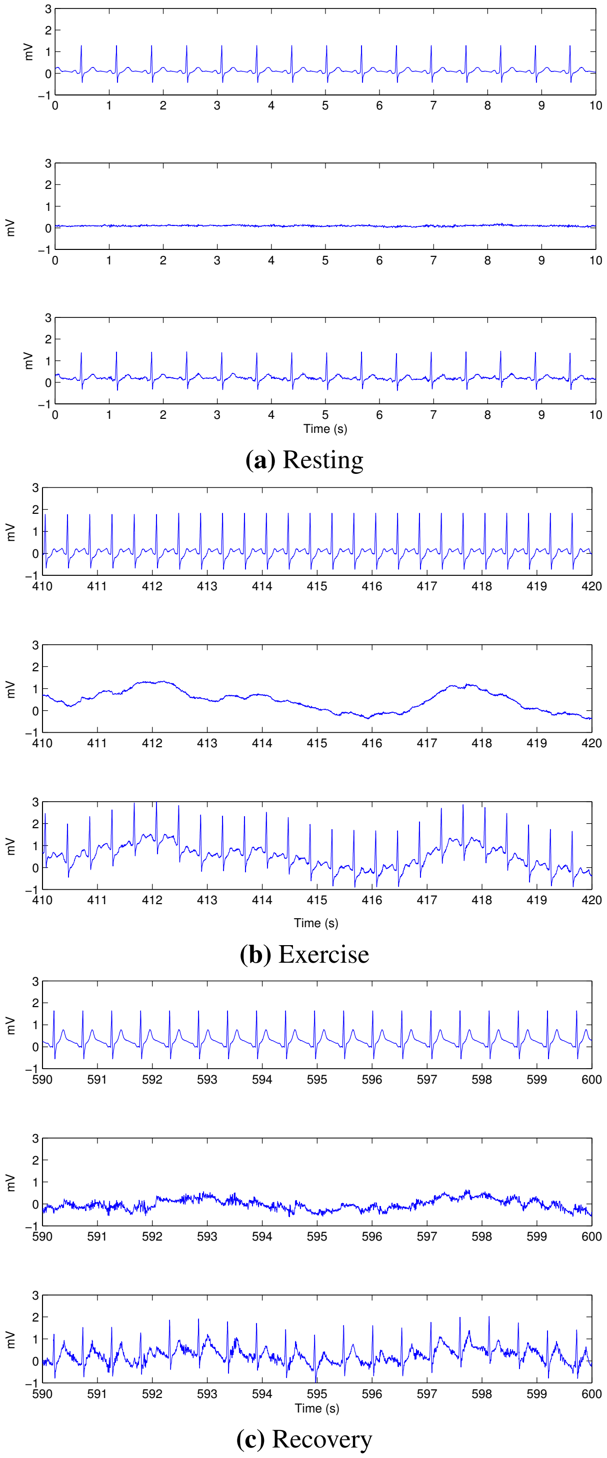

Figure 3. 10-second-fragments of simulated stress test records (noiseless ECG, noise and noisy ECG) during **(a)** resting, **(b)** exercise and **(c)** recovery phases.

beats (*templates*) extracted from exercise and recovery phases of a real exercise test recording. The HR and ST depression of each *template* were modified to follow a known ST/HR pattern. Then, a continuous signal was obtained concatenating *templates*' repetitions, smoothed so that HR and ST depression varied linearly between the modified *templates*' values. The final simulated ECG had a duration of approximately 11 minutes.

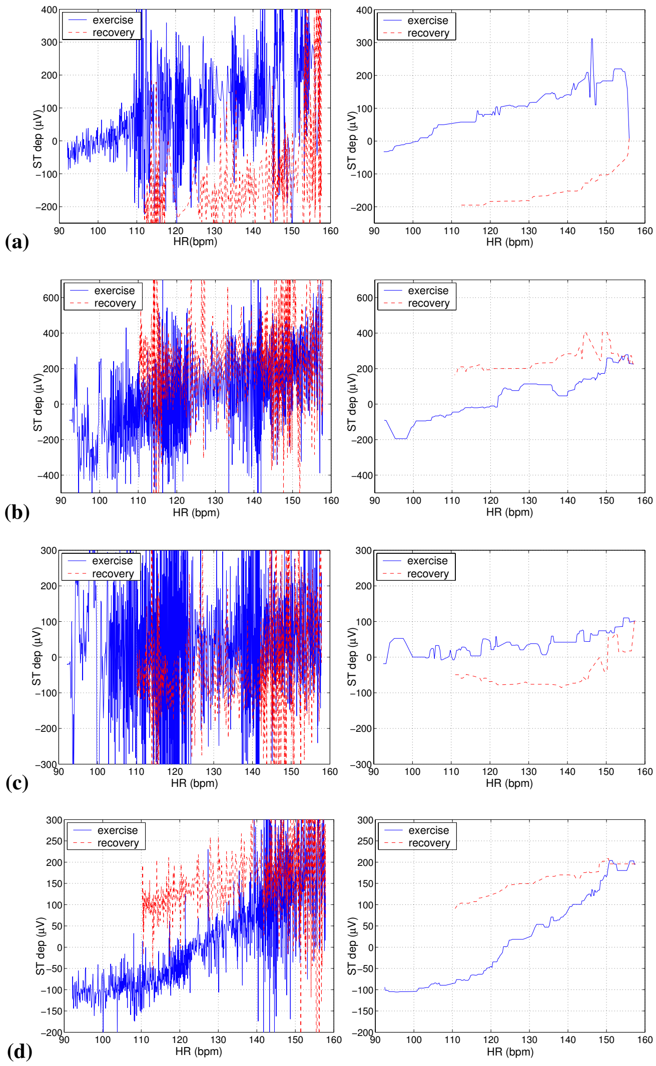

Figure 4. ST/HR diagram. **Left:** Before processing. **Right:** After processing. [original ST/HR hysteresis, estimated ST/HR hysteresis, RMS noise] (all in μV). **(a)** [-281, -289, 472], **(b)** [118, 137, 572], **(c)** [-83, -97, 333], **(d)** [73, 81, 223].

Exercise test noise records were estimated by subtracting from each beat of actual exercise test recordings (different from the one used to construct the simulated ECG) its corresponding averaged beat. Due to beat-to-beat morphological variations noise estimated records may include QRS components. In order to cancel the spikelike residual QRS artifacts, that do not emulate real noise, a similar procedure based on the MAD method previously described was applied. Rejected samples were substituted by a random value within the threshold limits.

Finally, simulated noisy ECGs were constructed by simply adding ECG and noise records. Fig. 3 shows fragments of 10-second duration of the simulated records at different stages of the exercise test (resting, exercise and recovery, respectively).

4. Results

The proposed method was evaluated on a total of 216 records. We used 4 different ST/HR diagram patterns, based on actual cases reported in previous works [2], and 54 different noise records with RMS levels ranging from 114 to 979 μV, extracted from different leads of real exercise test recordings.

Evaluation was performed by comparing the ST/HR diagrams of the noiseless simulated signals with the noisy/denoised ones, assuming that the QRS fiducial point alignment is stable enough to maintain beat marks unmodified. To assess the method performance, an estimation error trend ($e_i = \widehat{ST_i} - ST_i$) was computed as the difference in ST measurements between the noisy/denoised trends ($\widehat{ST_i}$) and the noiseless series (ST_i).

The method proposed here achieved a reduction in the standard deviation of the estimation error of 76.38% (from 271 to 63 μV). The absolute error ($|e|$) decreased from 168 to 37 μV in mean (77.98%). Fig. 4 illustrates the noise reduction in ST/HR diagrams obtained by our method for the different patterns.

Although it can be appreciated, both visually and numerically, the improvement in ST/HR diagram achieved by the processing, we did not get a significant reduction in the estimation error of the ST/HR hysteresis (15.85% in standard deviation, from 63 to 53 μV, and 14.71% in mean, from 34 to 29 μV), which may indicate that the ST/HR hysteresis is itself a robust measure in very noisy ST/HR diagrams.

5. Discussion and conclusions

The high muscular activity developed during exercise test causes extremely noisy ECG recordings; as a result, clinical indexes automatically computed from them, particularly those based on the ST value, might be unreliable. In this work we have presented a robust method to automatically estimate the ST/HR hysteresis from a ST/HR diagram constructed only from reliable measures, according to an adaptive noise threshold rejection procedure. The improvement achieved on noisy ST/HR diagrams is significant, visually and numerically, and enables those ST/HR diagrams to be used as clinical diagnostic tools themselves, which would be impossible before the processing. Our results suggest that the ST/HR hysteresis is itself a robust measure in noisy ST/HR diagrams, which may explain why it has shown to be the most significant diagnostic variable among all the indexes extracted from the ST/HR diagram.

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