Amplitude Change in R and T Waves of Exercise Electrocardiogram

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Introduction

The exercise test is performed to evaluate the presence in the electrocardiogram (ECG) of myocardial ischaemia. In multistage Bruce protocol the patient on a bicycle ergometer is subject to a workload linearly increasing in time (25 W every 2 minutes). The exercise is stopped when the heart rate reaches a maximum (acme). The standard 12-leads ECG is recorded using the electrocardiograph PC-ECG 1200 (Norav Medical Ltd.), with resolution of 2.441μV and 500 Hz sampling frequency.

Exercise ECG

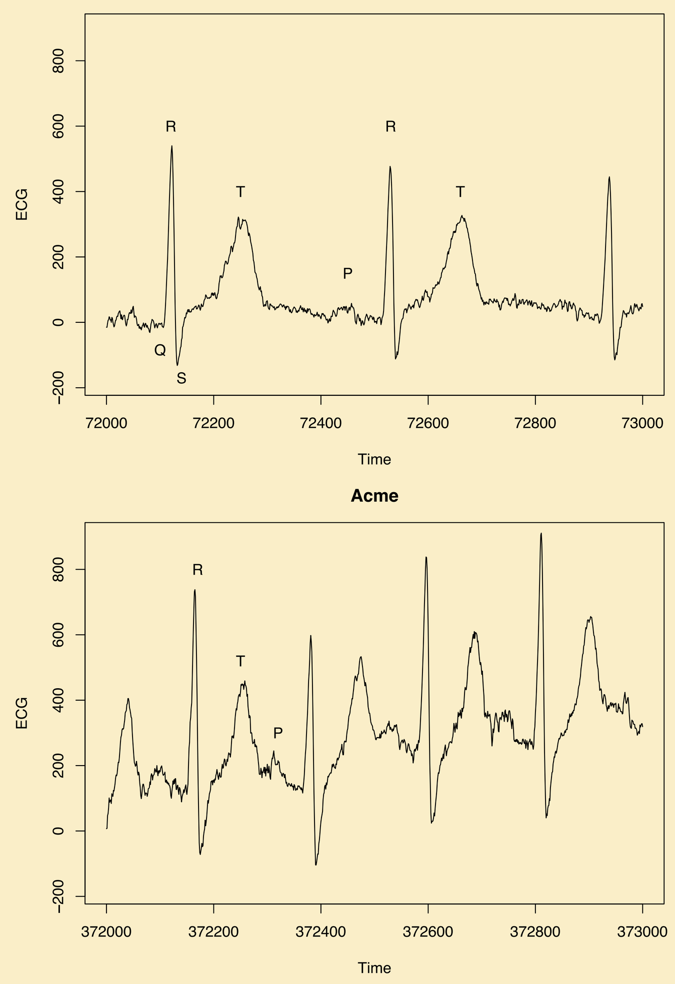

Figure 1: ECG at rest and acme (sampling units).

Mathematical Model

The R and T waves amplitudes are measured from the ECG for each beat. These series are modeled by $X_i(t) = \mu(t) + Z_i(t)$ where $i = 1, ..., n$ is the index of the subject; $t = 1, ..., m$ is the time index (beat number); $\mu(t)$ is the population mean; $Z_i(t)$ are independent realizations of the processes $Z(t)$, with zero mean, Var $Z(t) = \sigma(t)^2$ and covariance matrix C, representing error measurement and random individual deviations from the population mean.

The series are normalized dividing by their temporal mean to show relative variation during time. Each series X_i is smoothed expanding it in an orthogonal basis of splines, giving $X_i^{(s)}$.

The estimated population mean is $\hat{\mu}(t) = \sum_i X_i^{(s)}(t)/n$ and the estimated variance of $Z(t)$ is $\hat{\sigma}(t)^2 = \sum_i (X_i^{(s)}(t) - \hat{\mu}(t))^2/(n-1)$.

The simultaneous confidence band of level $1-\alpha$ of the population mean $\mu(t)$ is

$$\hat{\mu}(t) \pm \hat{\sigma}(t)\ M_{1-\alpha}\ n^{-1/2}$$

where $M_{1-\alpha}$ is the quantile of the r.v.

$$M = \max_{t=1,...,m} |Z(t)|/\hat{\sigma}(t)$$

The resulting bands are in fig.3 (left).

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SiZer - Significant Zero Crossing of derivative

This method estimates the population mean $\mu(t)$ of raw data series and its derivative using a model 'trend plus noise' $Y(t) = \mu(t) + W(t)$ where $Y(t) = \frac{1}{n}\sum_{i=1}^{n} X_i(t)$ and the noise is $W(t) = \frac{1}{n}\sum_{i=1}^{n} Z_i(t)$.

A sequence of second order polynomials $P_j(t) = \beta_0^{(j)} + \beta_1^{(j)}(t-t_j) + \beta_2^{(j)}(t-t_j)^2;\ j = 1, ..., k$ is fitted locally to $Y(t)$ by minimization of the cost function $\sum_t (Y(t) - P_j(t))^2 w_j(t)$; $w_j(t) = K((t-t_j)/h)/\sum_t K((t-t_j)/h)$ is a Gaussian kernel and the bandwidth h acts as a smoothing parameter.

The theory of multivariate linear models provide both an estimate and a confidence interval for the polynomial coefficients $\beta^{(j)}$. The coefficients $\beta_0^{(j)}, \beta_1^{(j)}, j = 1, ..., k$ provide respectively an estimator of $\mu(t)$ and of its derivative. Their confidence intervals allow to construct the confidence bands as in fig. 3 (right).

Results

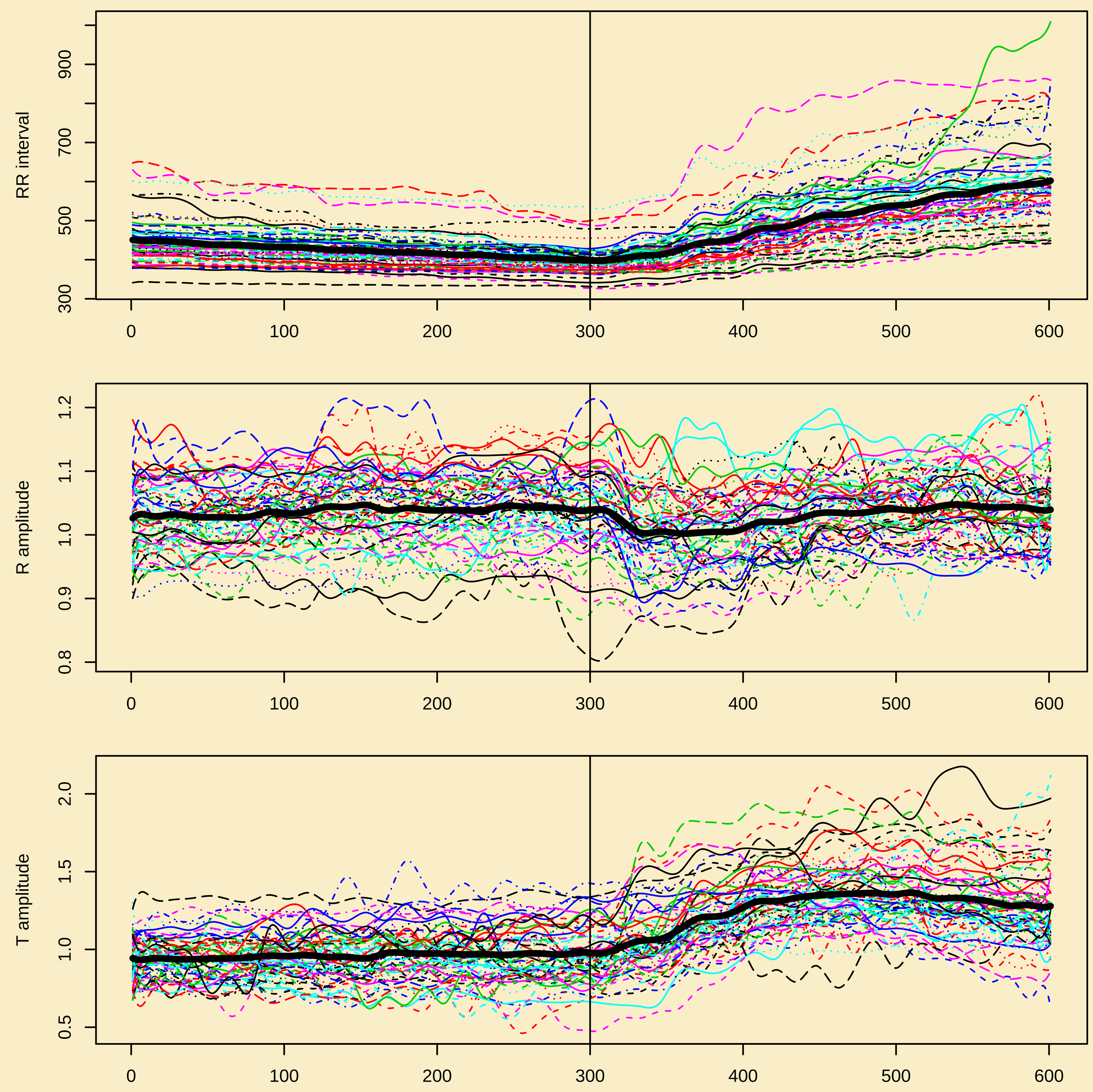

Figure 2: Functional data of: RR interval (top), R wave amplitude (middle), T wave (bottom) and their population means (thick black line) in a window centered at the acme (vertical line); x-axis: beat number; y-axis: RR ms; R and T amplitude normalized units.

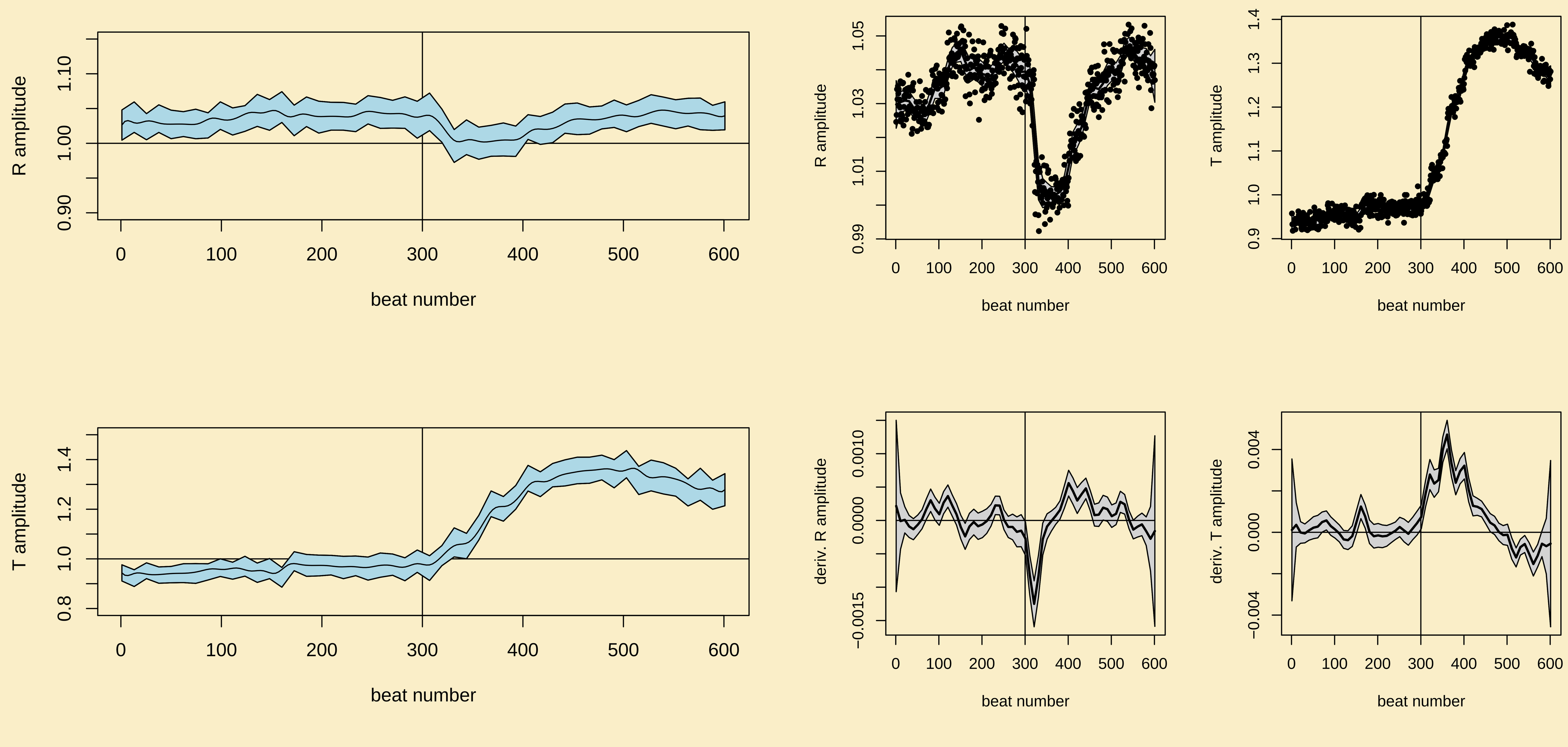

Figure 3: Left: Simultaneous confidence band of R and T population means, compared to the constant line of height 1 in a window centered at the acme (vertical line). Right: R and T population means (top) and zero crossing of the derivative (bottom) with confidence bands; y-axis: normalized untis.