Mental Stress Detection Using Cardiorespiratory Wavelet Cross-Bispectrum

Spyridon Kontaxis[1,2], Jesús Lázaro[2,1], Alberto Hernando[4,2], Adriana Arza[3,1], Jorge Mario Garzón[3], Eduardo Gil[2,1], Pablo Laguna[2,1], Jordi Aguiló[3,1], Raquel Bailón[2,1]

[1]CIBER de Bioingeniería, Biomateriales y Nanomedicina (CIBER-BBN), Spain
[2]BSICoS Group, I3A, IIS Aragón, University of Zaragoza, Spain
[3]Microelectronics and Electronic Systems Dept., Autonomous University of Barcelona, Spain
[4]Centro Universitario de la Defensa (CUD), Academia General Militar (AGM), Zaragoza, Spain

Abstract

In this work quadratic phase coupling between respiration and heart rate variability (HRV) has been studied during emotional and mental stress using wavelet cross-bispectrum (WCB). A total of 80 healthy volunteers subjected to a standard stress protocol have been analyzed. Some features derived from the WCB, such as the frequencies at which the maximum peak is located, the distribution of the dominant peaks and the phase entropy have shown statistical significant differences between stress and relax stages. A support vector machine classifier based on these features discriminates stress stages from relax ones with an accuracy ranging from 68 to 89%, suggesting that the interactions between respiration and HRV are altered during stress and may be used to assess it.

1. Introduction

Stress consists in a general adaptation syndrome "described as the non-specific response of the body to any demand on it" [1]. Stress is a highly subjective phenomenon and indeed many factors, including personality ones, will modulate the perception of stress and the arousal caused by the stressor. In an attempt to obtain an objective measure of stress, a variety of studies have proposed physiological markers including blood pressure (BP), heart rate (HR), various indices of heart rate variability (HRV) and respiration [2–4].

HRV is a non-invasive technique, which provides an indicator of Autonomic Nervous System (ANS) activity. A typical power spectrum has main frequency components such as the Low Frequency component (LF: 0.04-0.15 Hz) that is mediated by both sympathetic and parasympathetic systems and the High Frequency component (HF: 0.15-0.4 Hz) that reflects the Respiratory Sinus Arrhythmia (RSA) and is mainly mediated by parasympathetic systems [5].

In [4] the inclusion of respiratory frequency information in HRV analysis improved the ability of HRV to discriminate stress, which motivates the analysis of the relationship between respiration and HRV during stress. Different methods have been applied to investigate cardiorespiratory interactions [6]. In this work we propose to use the Wavelet Cross Bispectrum (WCB), to take into account the possible nonlinear relationship between respiration and cardiovascular system, as suggested in [7], and the non stationarity of the signals under stress [8].

2. Materials and methods

2.1. Database

A data base of 80 healthy volunteers (40 men and 40 women), who had not been diagnosed with any chronic disease or psychopathology, with an age of 21.57 ± 3.97 was recorded in the Autonomous University of Barcelona and University of Zaragoza. The protocol included two sessions, basal and stress, that were performed on different days but at the same hour for each participant [4]. The basal session is an autogenic relaxation condition that is divided in two parts for comparison with the other session: the first 10 minutes is a baseline stage (BL_B) and the next 25 min is a relaxing stage (RS). The stages of stress session are the following:

i. Basline stage (BL_S): A 10-minutes length autogenic relaxation condition.
ii. Story Telling (ST): 3 stories with a great amount of details were told to the subject, who was requested to remember as much details as possible.
iii. Memory Task (MT): The subject had to reiterate aloud all the remembered details about the 3 stories.
iv. Stress Anticipation (SA): The subject was instructed to wait alone during 10 minutes for the evaluation of the previous task.
v. Video Exposition (VE): The presentation of a video clip from the subject performance in MT was shown. A video of an actor remembering all the details was

displayed before that, trying to make the subject believe that his/her performance was very low.

vi. Arithmetic Task (AT): The subject had to perform in 5 minutes successive subtractions of 13, starting from the number 1022 and in case of a calculation error, the countdown was restarted from the beginning.

Only the last five stages of the Stress Session are considered stressful. In order to avoid possible transient phenomena between the different stages, only the six central minutes in the stages BL_B, RS, BL_S and SA are analyzed. In this approach the MT and AT are not examined due to the fact that the interpretation of results would be difficult while the subject was speaking.

A Medicom system, ABP-10 module (Medicom MTD Ltd, Russia), was used for recording respiratory signal (chest-band based) at 250 Hz and 3 orthogonal leads of the ECG signal, at 1 kHz. The HRV signal was generated from the beat occurrence time series, detected on Z-lead of the ECG, based on the integral pulse frequency modulation (IPFM) model, which accounts for the presence of ectopic beats [9] and sampled at a sample frequency (f_s) of 4 Hz. The respiration signal was downsampled to 4 Hz. HRV and respiration were filtered, with a pass-band filter (Butterworth 6th order with cutoff frequencies of 0.04 and 0.8 Hz). Both signals were normalized to have the same energy.

2.2. Wavelet Cross-Bispectrum (WCB)

A generalization of bispectral analysis leads to Wavelet Cross-Bispectrum (B_{WCB}) that consists of wavelet biamplitude (A_{WCB}) and wavelet biphase (ϕ_{WCB}) [10]:

$$\begin{aligned} B_{\text{WCB}}(f_1,f_2) &= \int_T W_x(f_1,\tau) W_y(f_2,\tau) W_x^*(f_{12},\tau)\, d\tau \\ &= A_{\text{WCB}}(f_1,f_2)\, e^{j\phi_{\text{WCB}}(f_1,f_2)} \end{aligned} \quad (1)$$

where $f_{12} = f_1 + f_2$. The integration is done over a finite time interval $T : \tau_0 \leq \tau \leq \tau_1$. The $W_x(f,\tau)$ and $W_y(f,\tau)$ in (1) are the Continuous Wavelet Transform (CWT) coefficients and are given by:

$$W_x(f,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t)\, \psi^* \left(\frac{t-b}{a} \right) dt \quad (2)$$

where $\psi(t)$ is the mother wavelet scaled by a factor a, $a>0$, and dilated by a factor b. The frequencies could be interpreted as inverse scales, i.e. $a = f_c f_s / f$ where f_c is center frequency of the mother wavelet and f_s the sampling frequency.

The signal $x(t)$ corresponds to the HRV signal and $y(t)$ is the respiration signal, so the WCB measures, in the finite time interval T, the amount of Quadratic Phase Coupling (QPC) that occurs between components of HRV at frequency f_1, components of respiration at frequency f_2 and components of HRV at frequency $f_1 + f_2$. Thus, the WCB can be considered a measure of cardiorespiratory coupling. Due to the symmetries in the definition and the limitation set by f_s the WCB estimation is done in the region $\Omega : f_1 + f_2 \leq f_s/2$.

The different stages of the experiment have different durations. In order to have the same resolution in all of them the WCB is computed in segments of duration (T) 50 ± 2.5 sec with an overlap of 12.5 ± 2.5 sec. Regarding the implementation of CWT the complex Morlet wavelet was used with bandwidth parameter $f_b = 0.5$ Hz and center frequency $f_c = 0.3$ Hz. These values were selected based on the frequency content of cardiovascular and respiratory oscillations.

2.3. Cardiorespiratory features

Different features are computed for each segment. The final feature set consists of the mean of the features' values in all the segments for each stage. The features that are related to the wavelet biamplitude are the following:

$$(f_{\text{HRV}}, f_{\text{R}}) = \underset{f_1, f_2}{\operatorname{argmax}} \{A_{\text{WCB}}(f_1, f_2)\} \quad (3)$$

Then, the M local maxima, which are at least higher than half of the $A_{\text{WCB}}(f_{\text{HRV}}, f_{\text{R}})$, are detected and denoted $(f_{\text{HRV}_i}, f_{\text{R}_i})$. Subsequently, the mean distance (D_{M}) of the M local maxima to absolute maximum is computed:

$$D_{\text{M}} = \frac{1}{M} \sum_{i=0}^{M-1} \sqrt{(f_{\text{HRV}} - f_{\text{HRV}_i})^2 + (f_{\text{R}} - f_{\text{R}_i})^2} \quad (4)$$

Note that D_{M} remains a feature which measures the energy distribution around the absolute maximum. The next feature is related with the wavelet biphase and it is called phase entropy (P_e). The $\phi_{\text{WCB}}(f_1, f_2)$ is quantized in N bins sized $2\pi/N$ radians, indexed by $\mathcal{B}_n$ ($n = 0, ..., N-1$), with N being the number of samples in the interval T. Then, a relative histogram $p(\mathcal{B}_n)$ (Figure 1) is computed by dividing the number of elements in each bin $\mathcal{B}_n$ by the total number, L, of possible pairs (f_1, f_2) which compose the domain Ω. The next step is to calculate the Shanon entropy, which is a measure of randomness and it is taken as a feature [11]:

$$P_e = -\sum_{n=0}^{N-1} p(\mathcal{B}_n) \;\; log(p(\mathcal{B}_n)) \quad (5)$$

2.4. Statistical analysis and classification procedure

A statistical analysis was performed for the cardiorespiratory features. A Student Test or a Wilcoxon paired statistical test is implemented depending on the distribution of the data, Gaussian or not, respectively. The purpose

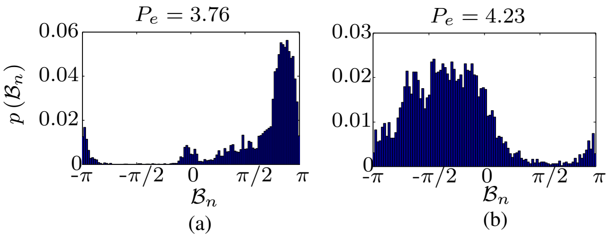

Figure 1. The histograms for (a) relax, (b) stress stage

of this analysis is to find statistical differences in feature's values between stress (ST, SA, VE) and relax (BL_S) stages within the same subject (paired test) and day. Furthermore, the two relax stages from the same subject but on different days (BL_S, BL_B) were compared to test the repeatability of the measurement.

Then, we approached the problem of classification of each stage as stressful or relaxing. All stress stages (ST, SA, VE) were pooled together to form the stress group, while the relax stage of basal session (RS) formed the relax group. The rationale for using (RS) instead of BL_S and BL_B was that it had a similar timing within the session as stress stages. In order not to over-fit the classifier, only the three most significant features were used. A Support Vector Machines classifier (SVM) was used (Gaussian radial basis kernel, scaling factor $\sigma = 1$). A 3-fold cross-validation scheme was adopted and repeated 50 times. The classification performance was evaluated through the classification accuracy rate (CA), that is the number of corrected predictions divided by the total number of predictions, averaged for the total number of repetitions and the metric F-measure or F1 score (F1), that is the harmonic mean of precision (true positives divided by the sum of true positives and false positives) and recall(true positives divided by the sum of true positives and false negatives) averaged for the total number of repetitions.

3. Results

Table 1 shows the p-values of statistical paired tests. Each comparison BL_B, ST, SA, VE vs BL_S was done individually, maximizing the number of subjects in each comparison (37, 40, 44, 44 respectively). The reduced number of the subjects in each comparison is due to the rejection of respiration signals with motion artifacts in different stages. The Wilcoxon tests are marked with different color and when the null hypothesis was not rejected is marked with "–".

Table 2 shows the results of the classification problem. For each stage of the classification procedure, i.e. ST, SA, VE, RS all the possible subjects (47, 52, 53, 57 respectively) with measurements were selected.

The Figure 2 represents the boxplots for the features that had been used in the classification procedure in each stage.

Table 1. The p-values of statistical paired tests

	Cardiorespiratory Features		
Stages	f_R	D_M	P_e
BL_B vs BL_S	–	–	–
ST vs BL_S	$4.73{\cdot}10^{-14}$	$3.15{\cdot}10^{-8}$	$1.55{\cdot}10^{-6}$
SA vs BL_S	$6.04{\cdot}10^{-5}$	$4.03{\cdot}10^{-6}$	$1.41{\cdot}10^{-5}$
VE vs BL_S	$1.09{\cdot}10^{-7}$	$5.03{\cdot}10^{-5}$	$2.06{\cdot}10^{-9}$

Table 2. The metrics CA and F1 for the SVM classifier

	Metrics	
Stages	CA $\pm$ std(%)	F1 $\pm$ std(%)
ST vs RS	89.37±3.65	88.25±4.07
SA vs RS	67.89±5.65	66.45±6.06
VE vs RS	85.82±4.71	84.94±5.11

4. Discussion

In this paper changes of QPC of HRV and respiration during stress have been investigated, in particular through features f_R, D_M, and P_e. Based on the results of statistical analysis (Table 1) the three selected features have the capacity to discriminate between stress and relax stages. Two of them, ST and VE, have the most significant differences respect to basal. In the SA stage, the subject was waiting for the evaluation of previous tasks, in contrast with the ST and VE stages, wherein there was a specific stressful stimuli. The absence of a specific stressful stimuli in SA could imply that SA is less stressful than ST and VE, and that could explain the lower significant differences. No significant differences were found between the two relaxing stages (BL_S, BL_B).

Results of classification (Table 2), suggest that the selected features have discriminant power in the stress conditions ST (CA=89.37%) and VE (CA=85.82%) rather than SA. Figure 2 shows that the index f_R tends to get higher values in stress stages (ST, VE). Furthermore, regarding D_M, the local maxima representing other significant couplings between frequency components are closer to the maximum peak in the relax conditions than in stress, fact that is compatible also with the P_e feature. The P_e is lower (relax) when the process tends to be harmonic, while is increased (stress) when the process becomes more random.

5. Conclusion

This work has studied changes in quadratic phase coupling between respiration and HRV during emotional and

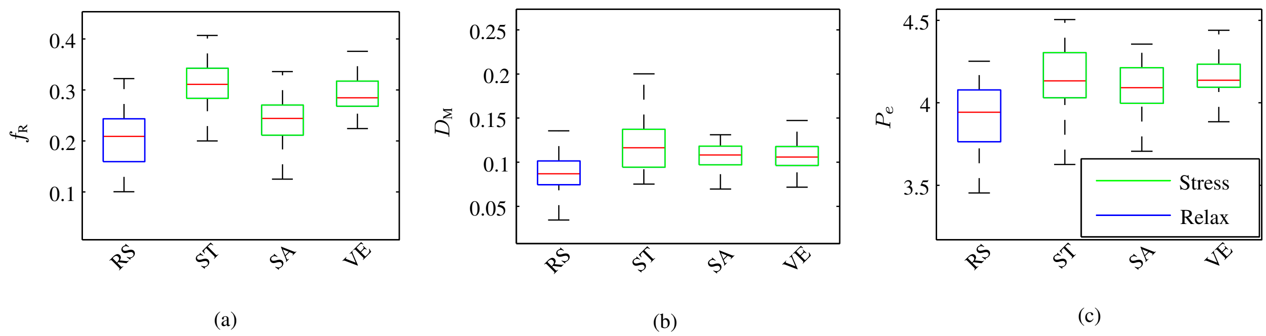

Figure 2. The boxplot for the feature (a) f_R, (b) D_M, (c) P_e

mental stress using wavelet cross- bispectrum (WCB). Some features derived from the WCB have shown statistical significant differences between stress and relax stages. Among them one feature related to respiratory frequency achieved the best results (p-value $< 10^{-13}$). Classification based on features related to respiratory frequency, the energy distribution around the maximum peak and phase entropy discriminates ST from relax with 89% accuracy and VE with 86%. These results supports that the interactions between respiration and HRV are altered during stress and may be used to assess it.

6. Acknowledgment

This work is supported by Universidad de Zaragoza under fellowship UZ2014-TEC-01 by Ministerio de Economía y Competitividad (MINECO), FEDER; under projects FIS-PI12/00514 and TIN2014-53567-R, by CIBER in Bioengineering, Biomaterials & Nanomedicine through Instituto de Salud Carlos III, and by Grupo Consolidado BSICoS from DGA (Aragón) and European Social Fund (EU).

References

[1] Selye H. The stress of life, 1957.

[2] Vrijkotte TG, Van Doornen LJ, De Geus EJ. Effects of work stress on ambulatory blood pressure, heart rate, and heart rate variability. Hypertension 2000;35(4):880–886.

[3] Grossman P. Respiration, stress, and cardiovascular function. Psychophysiology 1983;20(3):284–300.

[4] Hernando A, Lázaro J, Gil E, Valdes AA, Garzon-Rey J, López-Antón R, de la Cámara C, Laguna P, Aguiló J, Bailón R. Inclusion of respiratory frequency information in heart rate variability analysis for stress assessment. IEEE Journal of Biomedical and Health Informatics 2016;20(4):1016–1025.

[5] Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology. Heart rate variability: standards of measurement, physiological interpretation and clinical use. Circulation 1996; 93(5):1043–1065.

[6] Pompe B, Blidh P, Hoyer D, Eiselt M. Using mutual information to measure coupling in the cardiorespiratory system. Engineering in Medicine and Biology Magazine IEEE 1998;17(6):32–39.

[7] Novak V, Novak P, de Champlain J, Le Blanc AR, Martin R, Nadeau R. Influence of respiration on heart rate and blood pressure fluctuations. Journal of Applied Physiology 1993; 74(2):617–626.

[8] Jamšek J, Stefanovska A, McClintock PV. Nonlinear cardio-respiratory interactions revealed by time-phase bispectral analysis. Physics in medicine and biology 2004; 49(18):4407.

[9] Mateo J, Laguna P. Analysis of heart rate variability in the presence of ectopic beats using the heart timing signal. Biomedical Engineering IEEE Transactions on 2003; 50(3):334–343.

[10] Van Milligen BP, Sanchez E, Estrada T, Hidalgo C, Brañas B, Carreras B, Garcia L. Wavelet bicoherence: a new turbulence analysis tool. Physics of Plasmas 1994 present 1995; 2(8):3017–3032.

[11] Chua KC, Chandran V, Acharya R, Lim C. Higher order spectral (hos) analysis of epileptic eeg signals. In Engineering in Medicine and Biology Society, 2007. EMBS 2007. 29th Annual International Conference of the IEEE. IEEE, 2007; 6495–6498.

Address for correspondence:

Spyridon Kontaxis

Dep. Ingeniería Electrónica y Comunicaciones. Universidad de Zaragoza, C/ María de Luna 1, 50018 Zaragoza, Spain
sikontax@gmail.com