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Time-Frequency Representation of Cardiovascular Signals during Handgrip Exercise

Suvi Tiinanen, Antti Kiviniemi, Mikko Tulppo, and Tapio Seppänen

Abstract—**Altering cardiovascular oscillation is present during various interventions, e.g. in autonomic tests. Traditional spectral analysis suffers from nonstationary data and poor time resolution when studying the dynamics and frequency of cardiovascular signals. Smoothed pseudo Wigner-Ville representation method was applied when analyzing handgrip (HG) data of healthy men (n=11). Prevalent low frequency (PLF) and LF/HF powers were estimated from the time-frequency representation (TFR). According to the experimental results, PLF increases during HG with both heart rate interval (RRi) and systolic blood pressure (SBP) data. In addition, TFR revealed the increasing LF power during the HG with both RRi and SBP, while HF power increases with SBP and decreases with RRi. This is interpreted as an altered sympatho-vagal balance during the hand grip protocol.**

I. Introduction

Cardiovascular signals such as heart rate interval (RRi) and arterial blood pressure (BP) oscillates at different frequencies, ranging from ultra low frequencies to high frequencies (from 0.0001Hz up to 0.5Hz in humans). Different oscillatory patterns are said to reflect a different branches of autonomic nervous system [1]. These oscillatory patterns have been popular among cardiovascular scientists for decades. Traditional spectrum analysis has been an important tool in studying oscillations of cardiovascular signals [2, 3]. Besides being a powerful tools, one drawback that traditional spectrum analysis suffers from, is the assumption of stationary data. During interventions such as autonomic tests and exercises, the data of measured variables is not necessarily stationary**,** and thus the traditional spectrum analysis methods should be applied carefully. One method to overcome the problem with nonstationary signals is newish time-frequency representation (TFR) methods [4, 5]. TFR methods are advantageous in getting both time and frequency resolution good, meaning that very fast changes can also be detectable.

Spontaneous fluctuation in arterial BP, Mayer waves, occurs at 0.1Hz frequency in humans [6]. Mayer waves are defined as fluctuation in arterial pressure slower than respiration that correlates most to peripheral sympathetic drive [7]. Mayer waves are also present in systolic blood pressure signal (SBP) and in RRi via the baroreflex loop. The control of heart rate is a complex system, parasympathetic nervous system decelerating and sympathetic system accelerating it. Due to the present Mayer wave in RRi, the origin of low frequency (LF, 0.04-0.15Hz) is the activation of the sympathetic branch. Parasympathetic activation, however, has also been found present in LF range [2]. Oscillation in high frequency (HF, 0.15-0.5Hz) area is originating mainly from respiration reflecting the parasympathetic branch of autonomic nervous system.

Although the amplitude of LF oscillation has been largely studied, the mechanism that shifts the peak frequency in LF range is unclear. The prevalent low frequency (PLF) is determined as the frequency of maximum power in energy spectrum [8]. An increased PLF of RRi oscillation in LF range has been observed among cardiac patients with a higher risk of cardiac death [8, 9]. Energy spectrum is traditionally calculated via an autoregressive (AR) model or Fast Fourier Transform (FFT) based method from data sequence at the minimum length of 2min assuming the data to be stationary [10]. The aims of this paper are the following:

1) Apply time-frequency representation method to analyze the LF spectral properties of RRi and SBP.
2) Study the dynamics and frequency of LF oscillations during intervention using TFR.

II. Methods

A. Data

The transient data for this study was obtained by static hangrip exercise (HG) test. The study population consisted of 11 healthy male volunteers (N=11, age 35±4 years, weight 79±8kg, height 178±4cm). The study was performed according to the Declaration of Helsinki, the Ethical Committee of the Northern Ostrobothnia Hospital District, Oulu, Finland, approved the protocol, and all the subjects gave a written informed consent. The subjects lay in a supine position in a quiet room for at least 15 minutes before data collection and were instructed to breathe at a constant metronome-guided frequency of 0.25 Hz at rest and during the test. Electrocardiogram (ECG), (TEC-7700, Nihon Kohden, Japan), continuous blood pressure from a finger of the non-exercising arm (Finapres, Ohmeda, USA) and respiration frequency data were collected with a PowerLab data acquisition system (PowerLab/8SP, ADInstruments, Australia) with a sampling frequency of 1,000 Hz.

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S. Tiinanen and T. Seppänen are with the Department of Electrical and Information Engineering, PO BOX 4500, 90014 University of Oulu, Finland (phone +358 8 553 2536; fax. +358 8 553 2612; e-mail: {suvi.tiinanen, tapio.seppanen}@ee.oulu.fi).
A.Kiviniemi and M. Tulppo are with Verve, Kasarmintie 13, P.O.Box 404, FI-90101 Oulu, Finland. email: {antti.kiviniemi, mikko.tulppo}@verve.fi.
PO BOX 404, 90101 Oulu, Finland (e-mail: {antti.kiviniemi, mikko.tulppo}@verve.fi)

In the first protocol stage, baseline data were collected for 5 minutes. In the second stage, static HG exercises were performed such that a subject holds a handgrip at 20% of voluntary contraction for 5 minutes. During HG, the sympathetic nervous system is activating, while the parasympathetic system is withdrawing.

R-peaks were detected automatically using custom made software with visual checking. Series of successive heart rate intervals (RRi) was then formed. Series of systolic blood pressure (SBP) values were obtained similarly (Fig. 2.). Both time series, RRi and SBP, were then linearly interpolated at the frequency of 2Hz and detrended using Savitzki-Golay filter (polynomial order 3. framesize 51) such that frequencies smaller than 0.04Hz were abolished. Signal analysis was performed with Matlab (The MathWorks Inc., Natick, MA).

B. Time-Frequency Representation (TFR)

Several TFR methods exist. One well-known technique used for analyzing of cardiovascular signals and applied in this study is the Wigner-Ville distribution (WVD) [11, 12]. The WVD is a Cohen's class high-resolution representation of the signal x(t) in time and frequency and defined as:

$$WVD(t,f) = \int x\left(t+\frac{\tau}{2}\right) x * \left(t-\frac{\tau}{2}\right) e^{-j2\pi f\tau} d\tau \quad (1)$$

Because of quadratic nature of x(t), there are cross-terms presence in WVD, which makes the interpretation of time-frequency content more difficult. Hence, we used smoothed pseudo WVD (SPWVD) instead:

$$SPWVD(t,f) = \int_{-\infty}^{\infty} h(\tau) \int_{-\infty}^{\infty} g(s-t)\, x\left(s+\frac{\tau}{2}\right) x * \left(t-\frac{\tau}{2}\right) e^{-j2\pi f\tau} ds d\tau \quad (2)$$

, where h(τ) and g(s-t) are frequency and time smoothing windows, respectively, that reduces the cross term effect. The Hamming smoothing windows were 41samples for time and 121 samples for frequency. Other window sizes were also tested, but this combination seemed to reach good resolution in both time and frequency with a reasonable amount of noise in spectrum. TFR was calculated using Time-Frequency toolbox [16].

C. Spectral indices

An estimate of the peak frequency in LF range (PLF) was obtained by the following algorithm: Firstly, the mean of all local TFR maxima values that were greater than 400ms2/Hz and 4mmHg/Hz for RRi and SBP, respectively, were calculated and defined as threshold values for PLF calculation. Secondly, the PLF for each TFR protocol stage was obtained as a mean frequency value from local TFR maxima that are greater than this threshold. In this way, the effect of noise-related variation in TFR is reduced. The indices which were selected for PLF calculation is plotted in Fig. 2 with red circles. As can been seen in Fig. 2, there are lots of activity in many frequencies of the LF range which may be due to complex regulating mechanism behind the HR and BP. Therefore we decided to estimate the PLF by averaging all the major peaks in the LF range.

TFR spectral power components were calculated as relative values in both LF and HF area. The total power of both bands is also given. In addition, an index describing the sympathovagal balance, LF/HF ratio, is calculated. All parameters were calculated for both RRi and SBP time series. Results are presented as means ± standard deviations and PLF results also as boxplots. Differences between protocols were tested with a Wilcoxon signed rank test. Values $p < 0.05$ were considered statistically significant. All statistics were calculated using SPSS® software (SPSS Inc, USA).

III. RESULTS AND DISCUSSION

TFR was displayed for illustration purposes as a 2-dimensional image plot where data is scaled to the full scale of RGB color map and as a 3-dimensional surface plot (Fig. 2.). Based on this visualization, the maximum sympathetic response is reached during the last two minutes of the HG test. Thus, the PLF and other spectral indices were calculated during that interval (HG(end)). To have a same range of data, the two minutes from baseline data were correspondingly chosen (Baseline). In addition, we analyzed the first two minutes of the handgrip test (HG(start)).

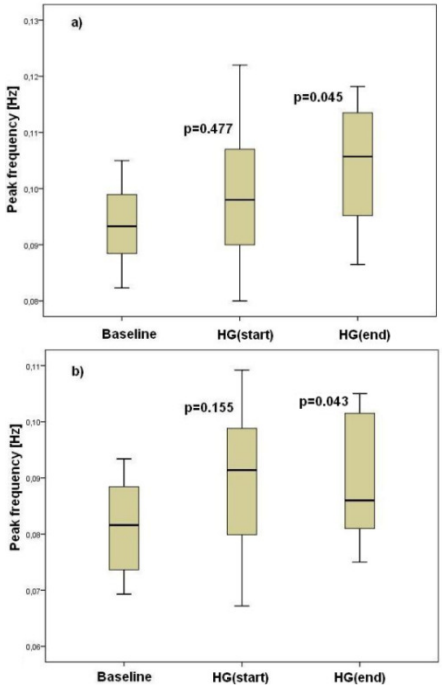

Fig. 1. Boxplots for PLF frequencies: a) RRi and b) SBP.

PLF values are presented as boxplots in Fig. 1. and numerically in Table I. PLF is increasing during the HG test and reaches the statistical significance ($p<0.05$) during the HG(end) for both RRi and SBP. Mean heart rates (HR) and SBP values are presented in Table I. Both HR and SBP increased during HG. Static HG exercise involves an increased arterial pressure and heart rate due to increased sympathetic activity and a vagal withdrawal [13][14]. Muscle metaboreflex is an interpretative mechanism increasing sympathetic activity during static exercise [15]. Our results indicate that during sympathetic activation, mainly caused by metaboreflex, frequency of oscillation tends to increase.

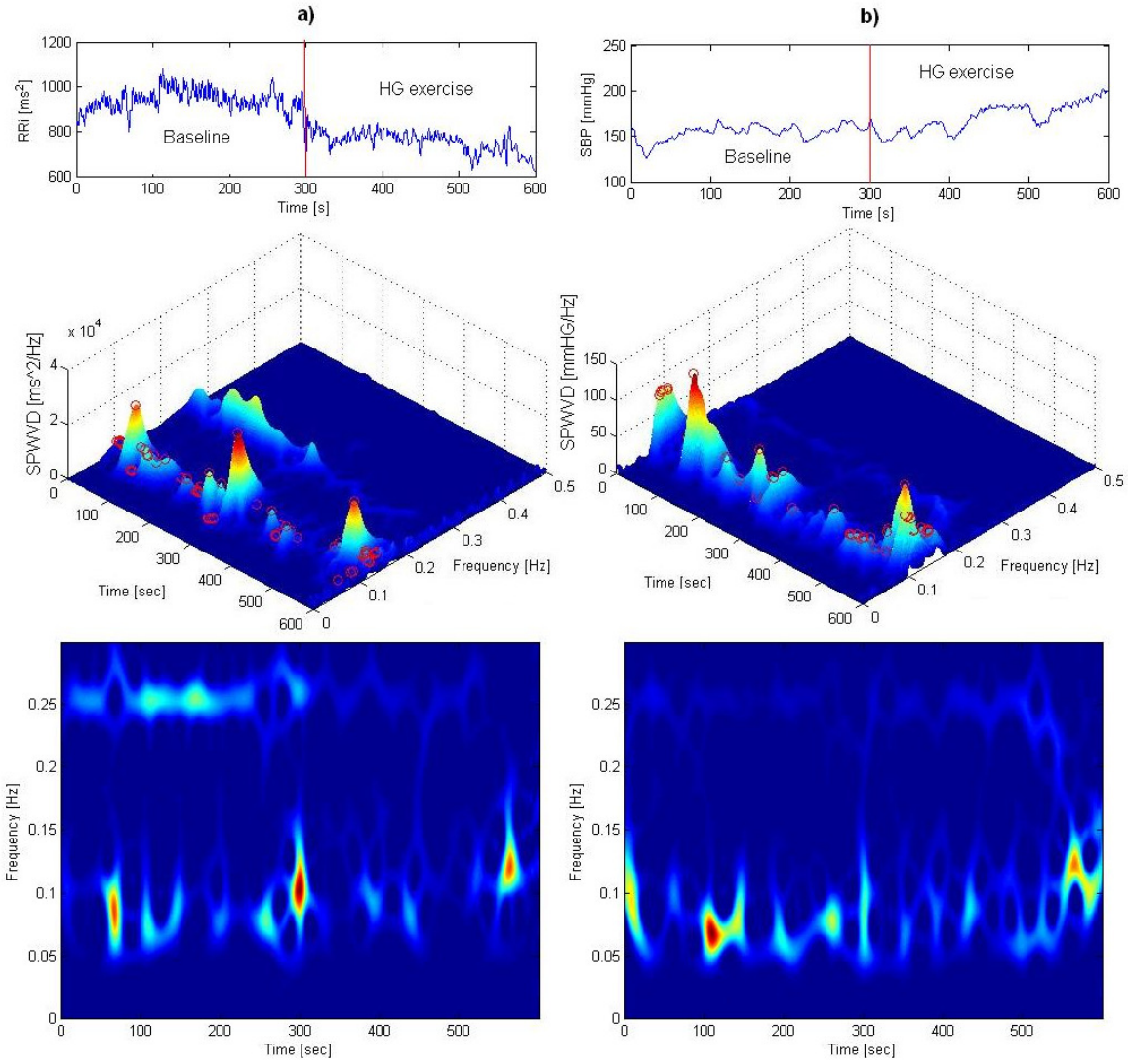

Fig. 2. Data presentation and SPWV distributions for: a) RRi and b) SBP signals.

TABLE I
CHARACTERISTICS AND SPECTRAL INDICES

Parameter	Baseline	HG(start)	HG(end)
HR [bpm]	62 ± 7	66 ± 8	70* ± 7
SBP [mmHg]	138 ± 9	152 ± 19	156* ± 11
PLF(RRi) [Hz]	0.093 ± 0.007	0.099* ± 0.01	0.103* ± 0.011
PLF(SBP) [Hz]	0.081 ± 0.009	0.089 ± 0.012	0.091* ± 0.011
LF(RRi) [%]	41 ± 15	46 ± 16	54* ± 17
HF(RRi) [%]	58 ± 15	53 ± 16	46*± 17
P(RRi) [ms2]	76076 ± 62990	47667 ± 18862	61349 ± 32688
LF(SBP) [%]	74 ± 12	77 ± 13	74 ± 15
HF(SBP) [%]	26 ± 12	23 ± 13	26 ± 17
P(SBP) [mmHg]	246 ± 144	227 ± 104	360 ± 204
LF/HF(RRi) [%]	81 ± 45	103 ± 65	143* ± 87
LF/HF(SBP) [%]	514 ± 363	663 ± 785	788* ± 430

* indicates $p < 0.05$ compared to baseline

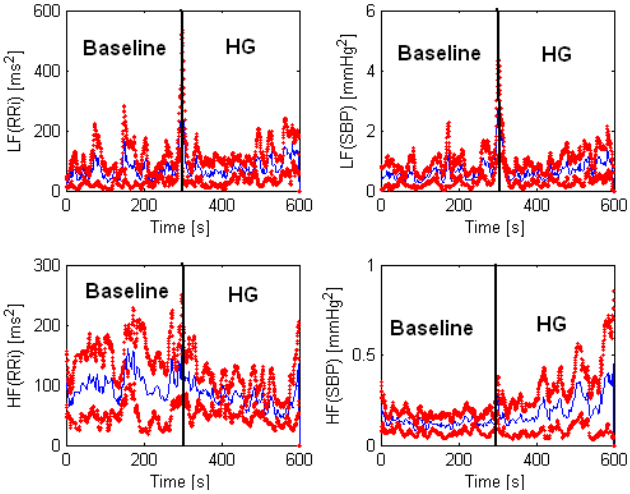

Fig. 3. Median LF and HF powers with 25% and 75% fractile curves extracted from TFR as a function of time.

Spectral indices are presented as means ± standard deviations in Table I. The median LF and HF components with 25% and 75% fractile curves as a function of time are presented in Fig. 3. Based on Fig. 3, the amplitude of RRi and SBP oscillation in LF range increased during the HG. RRi oscillation in HF range decreased, meaning the withdrawal of the parasympathetic branch. On the other hand, HF component of SBP slightly increased during the test. LF/HF ratio increased in both RRi and SBP signals during HG, indicating the shift to sympathetic activation.

IV. Conclusion

Smoothed pseudo Wigner-Ville representation method was applied when analyzing handgrip data of healthy men. Prevalent low frequency, LF and HF powers were estimated from the time-frequency representation.

According to the results obtained, PLF increases during HG with both heart rate interval and systolic blood pressure data. In addition, TFR revealed the increasing LF power during the HG with both RRi and SBP, while HF power increases with SBP and decreases with RRi. This is interpreted as an altered sympatho-vagal balance during the handgrip protocol.

References

[1] B. W. Hyndman, R. I. Kitney and B. M. Sayers, "Spontaneous rhythms in physiological control systems," *Nature,* vol. 233, pp. 339-341, Oct 1. 1971.

[2] S. Akselrod, D. Gordon, J. B. Madwed, N. C. Snidman, D. C. Shannon and R. J. Cohen, "Hemodynamic regulation: investigation by spectral analysis," *Am. J. Physiol.,* vol. 249, pp. H867-75, Oct. 1985.

[3] M. Pagani, F. Lombardi, S. Guzzetti, O. Rimoldi, R. Furlan, P. Pizzinelli, G. Sandrone, G. Malfatto, S. Dell'Orto and E. Piccaluga, "Power spectral analysis of heart rate and arterial pressure variabilities as a marker of sympatho-vagal interaction in man and conscious dog," *Circ. Res.,* vol. 59, pp. 178-193, Aug. 1986.

[4] M. B. Priestley, "Evolutionary Spectra and Non-Stationary Processes," *Journal of the Royal Statistical Society.Series B (Methodological),* vol. 27, pp. 204-237, 1965.

[5] L. Cohen, "Time-frequency distributions-a review," *Proceedings of the IEEE,* vol. 77, pp. 941-981, 1989.

[6] G. Preiss and C. Polosa, "Patterns of sympathetic neuron activity associated with Mayer waves," *Am. J. Physiol.,* vol. 226, pp. 724-730, Mar. 1974.

[7] C. Julien, "The enigma of Mayer waves: Facts and models," *Cardiovasc. Res.,* vol. 70, pp. 12-21, Apr 1. 2006.

[8] D. Wichterle, J. Simek, M. T. La Rovere, P. J. Schwartz, A. J. Camm and M. Malik, "Prevalent low-frequency oscillation of heart rate: novel predictor of mortality after myocardial infarction," *Circulation,* vol. 110, pp. 1183-1190, Sep 7. 2004.

[9] A. M. Kiviniemi, M. P. Tulppo, D. Wichterle, A. J. Hautala, S. Tiinanen, T. Seppanen, T. H. Makikallio and H. V. Huikuri, "Novel spectral indexes of heart rate variability as predictors of sudden and non-sudden cardiac death after an acute myocardial infarction," *Ann. Med.,* vol. 39, pp. 54-62, 2007.

[10] "Heart rate variability: standards of measurement, physiological interpretation and clinical use. Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology," *Circulation,* vol. 93, pp. 1043-1065, Mar 1. 1996.

[11] S. Pola, A. Macerata, M. Emdin and C. Marchesi, "Estimation of the power spectral density in nonstationary cardiovascular time series: assessing the role of the time-frequency representations (TFR)," *Biomedical Engineering, IEEE Transactions on,* vol. 43, pp. 46, 1996.

[12] M. O. Mendez, A. M. Bianchi, N. Montano, V. Patruno, E. Gil, C. Mantaras, S. Aiolfi and S. Cerutti, "On arousal from sleep: time-frequency analysis," *Med. Biol. Eng. Comput.,* vol. 46, pp. 341-351, Apr. 2008.

[13] F. Iellamo, P. Pizzinelli, M. Massaro, G. Raimondi, G. Peruzzi and J. M. Legramante, "Muscle metaboreflex contribution to sinus node regulation during static exercise: insights from spectral analysis of heart rate variability," *Circulation,* vol. 100, pp. 27-32, Jul 6. 1999.

[14] D. R. Seals, P. B. Chase and J. A. Taylor, "Autonomic mediation of the pressor responses to isometric exercise in humans," *J. Appl. Physiol.,* vol. 64, pp. 2190-2196, May. 1988.

[15] D. D. Sheriff, D. S. O'Leary, A. M. Scher and L. B. Rowell, "Baroreflex attenuates pressor response to graded muscle ischemia in exercising dogs," *Am. J. Physiol.,* vol. 258, pp. H305-10, Feb. 1990.

[16] Time–Frequency Toolbox [online]. http://tftb.nongnu.org