534. Relation in-between autonomic cardiovascular control and central nervous system activity during sleep using spectrum-weighted frequencies

E. Kaniušas[1], A. Podlipskytė[2], A. Alonderis[2], G. Varoneckas[2,3]
[1] Institute of Fundamentals and Theory of Electrical Engineering,
Bioelectricity & Magnetism Lab, Vienna University of Technology, Vienna, Austria
[2] Institute of Psychophysiology and Rehabilitation, Kaunas University of Medicine, Palanga, Lithuania
e-mail: *giedvat@ktl.mii.lt*
[3] Mechatronics Science Institute, Klaipėda University, Klaipėda, Lithuania

(Received 30 November 2009; accepted 03 February 2010)

Abstract. The present study is concerned with relevance of the spectrum-weighted frequencies of both heart rate variability (HRV) and electroencephalogram (EEG). The frequencies represent the balance point of power within a certain spectral range. The predictive value of the frequencies and their mutual interrelations are demonstrated with respect to different sleep stages based on data from a single case. In particular, the revealed stage-dependent relationships between frequencies from HRV and EEG suggest a close interrelation between autonomic cardiovascular control and activity of central nervous system. The results demonstrate that the easy-to-assess frequencies may provide a simple indicator of the sleep quality within the scope of comfortable patient monitoring.

Keywords: autonomic cardiovascular control, central nervous system, spectrum-weighted frequencies.

Introduction

Body activities are quantitatively assessed by the use of physiological indicators as blood pressure, temperature, and heart rate, the latter being derived from electrocardiography (ECG). Here the use of cardiorespiratory oscillations is of high importance, e.g., by monitoring heart rate variability (HRV) which reflects autonomic control of heart rate in a sophisticated way [1-3]. That is, HRV corresponds to activities of both body and central nervous system [1, 4]. On the other hand, mental activities, or generally speaking, activities of central nervous system, are registered by the use of electroencephalography (EEG). A special case of mental activity is given during sleep, which monitoring leads to sleep staging according to Rechtschaffen and Kales [5], and thus to a quantitative assessment of sleep efficiency. Usually investigation of sleep involves polysomnography (PSG) as the golden standard, requiring a high effort in both applied devices and attending (and scoring) physicians.

It should be noted that during human functioning a close relation between autonomic control of heart rate (reflected by HRV) and central nervous system (ECG) exists, especially during sleep when ambient factors do not have a prevailing influence. Therefore HRV might be used as a reflection of brain functions during sleep [6-8].

Obviously a low effort assessment of the body and mental activity is of high interest, combined with a minimal disturbance of the patient. Usually a high number of derived signals and elaborate signal processing methods are necessary to judge both activities, in particular during sleep [9, 10]. Thus, there is a need for more simple approaches. For instance, the authors in [11] have suggested the use of spectrum-weighted frequency f_W of EEG as an indicator of mental activity by utilizing shifts of f_W.

The rationale of the present study was to investigate the basic behaviour of f_W derived from HRV and EEG during sleep. In addition, possible mutual relations of f_W are investigated. Especially, established spectral ranges of HRV and EEG (Table 1) are taken into consideration in combination with separately considered sleep stages: awake before sleep (AW), rapid eye movements (REM), and drowsy to deep sleep stages (S1-S4).

Table 1. Absolute mean values of spectrum-weighted mean frequencies f_W from HRV and EEG for different sleep stages and all night.

Sleep stages/ total duration (min)	f_W from **HRV** (Hz)			
	Spectral ranges:			
	Total f_w^t 0.01-0.5 Hz	Humoral f_w^h 0.01-0.06 Hz	Sympathetic f_w^s 0.06-0.15 Hz	Parasympathetic f_w^p 0.15-0.4 Hz
Awake / 9	0.076	0.03	0.101	0.195
REM / 74	0.076	0.03	0.092	0.208
S1 / 0	-	-	-	-
S2 / 88	0.116	0.03	0.092	0.194
S3 / 32	0.128	0.03	0.092	0.201
S4 / 22	0.132	0.03	0.098	0.203
All night 225	0.104	0.032	0.093	0.201

Sleep stages/ total duration (min)	f_W from **EEG** (Hz)					
	Spectral ranges:					
	Total $f_w^{t'}$ 0.5-30.5 Hz	Delta f_w^{δ} 0.5-3.5 Hz	Theta f_w^{θ} 3.5-7.5 Hz	Alpha f_w^{α} 7.5-12.5 Hz	SMR f_w^{SMR} 12-15 Hz	Beta f_w^{β} 12.5-30.5 Hz
Awake / 9	6.85	1.39	5.13	10.15	13.37	20.43
REM / 74	5.34	1.61	5.09	9.54	13.48	19.03
S1 / 0	-	-	-	-	-	-
S2 / 88	4.18	1.39	5.07	10.06	13.54	16.7
S3 / 32	2.72	1.29	4.98	10.17	13.43	16.36
S4 / 22	2.45	1.29	4.97	10.2	13.45	16.13
All night 225	4.29	1.44	5.06	9.92	13.49	17.51

Methodology

Subject of the present study was a healthy male subject aged 31 with body mass index 32 kg/m^2. The subject was examined by means of conventional PSG including continuous monitoring of EEG (C3A2 derivation) and ECG. Genuine sleep stages were initially detected by means of standard PSG evaluation software (ALICE-4 Respironics) and then reassessed by an expert. The sampling rate of EEG was 100 Hz while that of ECG was 500 Hz.

HRV was assessed from a series of RR-intervals (= time distance between subsequent R-peaks in ECG). The RR-intervals were extracted by a well tested algorithm used for clinical purposes in the Institute of Psychophysiology and Rehabilitation (Palanga, Lithuania) over decades. Subsequently the series of RR-intervals were filtered automatically and reassessed manually by an expert to remove ectopic beats, arrhythmic events, and missing data, because the latter may significantly alter the estimation of the power spectral density p_H of HRV. Since the established sequence of the RR-intervals represents an irregularly time-sampled signal, the sequence was linearly interpolated with frequency F_I=3 Hz. The value of F_I was chosen to be higher than the highest instantaneous heart rate and sufficiently high that the Nyquist frequency (=F_I/2=1.5 Hz) of HRV-spectrum is not within the frequency range of interest (i.e., up to 0.5 Hz). The interpolation of the RR-sequence is demonstrated in Fig. 1a.

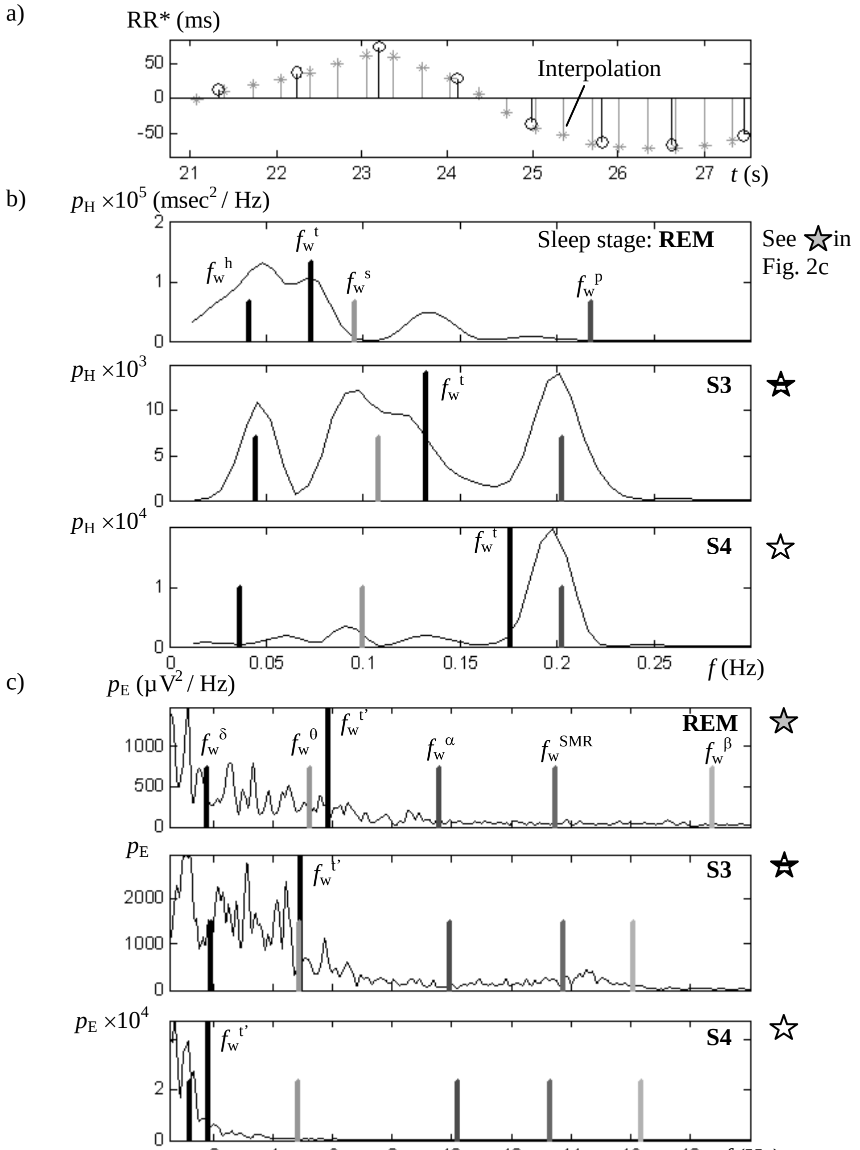

Fig. 1. Calculation of spectrum-weighted mean frequencies f_W. a) Interpolation of RR*-sequence with subtracted mean. b) Power spectral density p_H of HRV with indicated f_W in different spectral ranges (total spectral range f_w^t, humoral range f_w^h, sympathetic range f_w^s, and parasympathetic range f_w^p) during different sleep stages: rapid eye movements (REM) at t=100 min. according to Fig. 2c; sleep stage 3 (S3) at t=16 min., and sleep stage 4 (S4) at t=48 min. The sterns to the right visualize the relevant locations in the hypnogram from Fig. 2c. c) The corresponding power spectral densities p_E of EEG with indicated f_W (total spectral range $f_w^{t'}$, delta range f_w^{δ}, theta range f_w^{θ}, alpha range f_w^{α}, SMR range f_w^{SMR}, and beta range f_w^{β})

The values of p_H were estimated in absolute units (ms^2/Hz) using intervals of 60 s (180 points) with zero overlap, applying Hamming smoothing and zero padding up to 512 points.

Thus the resulting frequency resolution of p_H was about 0.006 Hz (=F_I/512), i.e., sufficiently fine to estimate p_H in the lowest humoral band (Table 1). In analogy to p_H, the power spectral density p_E of EEG was estimated in absolute units (μV^2 /Hz) using intervals of 10 s (1000 points) with 50 % overlap, applying Hamming smoothing and zero padding up to 2048 points. Here the attained frequency resolution was about 0.05 Hz (=100 Hz/2048), i.e., sufficiently fine to estimate p_E in the lowest delta band (Table 1).

Spectrum-weighted frequencies f_W were assessed for both HRV and EEC according to:

$$f_W = \int_{f\,min}^{f\,max} f \cdot dA \Bigg/ \int_{f\,min}^{f\,max} dA = \int_{f\,min}^{f\,max} f \cdot p \cdot df \Bigg/ \int_{f\,min}^{f\,max} p \cdot df \, , \qquad (1)$$

where f is the frequency, f_{min} and f_{max} are the lower and upper bounds of the relevant frequency range, respectively, and A is the area encompassed by p, i.e., by p_H or p_E (Fig. 1b, c). It can be derived from Eq. 1 that f_W represents the frequency of the center of A in the given frequency range [f_{min}, f_{max}]. The values of f_W were assessed for different frequency ranges, according to Table 1. The chosen ranges are widely accepted for HRV and EEG analysis in the clinical and research fields, and correspond to a particular physiological activity or sleep state [1]. The particular frequency range is given in the superscript of f_W according to Table 1.

Stationary RR-intervals were visually extracted by an expert before statistical measures of f_W (means, cross-correlation coefficients) were estimated (Table 1, 2). The resulting lengths of the stationary intervals per sleep stage are given in the first column of Table 1.

Results

Fig. 1b provides the course of p_H during three selected sleep stages (REM, S3, and S4). The stage is indicated in the right upper corner of each subfigure. Correspondingly, Fig. 2c illustrates the total sleep profile of the subject with indicated locations of the shown cases in Fig. 1b, c. It can be observed that during the active sleep stage REM the sympathetic activity prevails, whereas during the deepest sleep stage S4 the parasympathetic activity outweighs. The corresponding courses of p_E during the latter stages are given in Fig. 1c. For instance, it demonstrates that S4 is dominated by delta waves.

The locations of calculated f_W are indicated by thick vertical lines in each subfigure of Fig. 1b, c. It indicates that f_W^t, i.e., f_W concerning the total spectral range of HRV, strongly increases from REM to S4 by more than 100 % in the depicted case (Fig. 1b). Other changes – some of them being less significant – are summarized in Table 1. It shows absolute mean values of f_W considering separately particular sleep stages and the whole night. The observations can be given as follows:

i) f_W^t showed an increase by more than 70 % from AW (or REM) to S4 (e.g., 0.07 Hz/0.13 Hz for AW/S4),

ii) f_W^h concerning the humoral spectral range was nearly constant over all sleep stages (=0.03 Hz),

iii) f_W^s concerning the sympathetic spectral range indicated a slight decrease of about 10 % from AW to other sleep stages (e.g., 0.1 Hz/0.09 Hz for AW/S2),

iv) f_W^p concerning the parasympathetic spectral range showed a slight increase of about 4 % from AW to deep sleep stages (e.g., 0.19 Hz/0.2 Hz for AW/S4).

Fig. 1c demonstrates that $f_W^{t'}$, i.e., f_W concerning the total spectral range of EEG, strongly decreases from REM to S4 by more than 70 % in the given case. In parallel, the values f_W^{β} seem to decrease by about 15 %. The observations are summarized in Table 1, to give:

i) $f_W^{t'}$ showed a decrease by more than 60 % from AW to S4 (e.g., 6.8 Hz/2.4 Hz for AW/S4),

ii) f_W^{δ} concerning the delta spectral range showed a slight decrease of about 7 % from AW to deep sleep stages with REM showing the highest values (e.g., 1.6 Hz/1.3 Hz for REM/S4),

iii) f_W^{θ} concerning the theta spectral range showed no significant changes over all sleep stages (=5 Hz),

iv) f_W^{α} concerning the alpha spectral range showed a slight decrease of about 6 % from AW to REM with other sleep stages S1-S4 showing no decrease in comparison with AW (e.g., 10.1 Hz/9.5 Hz for AW/REM),

v) f_W^{SMR} concerning the SMR spectral range showed no significant changes over all sleep stages (=13.5 Hz), and

vi) f_W^{β} showed a decrease by about 20 % from AW (or REM) to S4 (e.g., 20.4 Hz/16.1 Hz for AW/S4).

Fig. 2a, b presents the time courses of a few selected f_W from HRV and EEG while the corresponding sleep staging (= hypnogram) is given in Fig. 2c. It is interesting to observe that f_W^t indicates an inverse behaviour to the hypnogram, deep sleep stages corresponding to increased values of f_W^t and reduced values to shallow (or active) sleep stages. This observation is in good agreement with the aforementioned data in Table 1. In analogy, the course of f_W^{α} is also inversely related to the hypnogram while that of f_w^{δ} and $f_w^{t'}$ show slight similarities with the hypnogram.

The resulting cross-correlation coefficients between f_W from HRV and that from EEG are given in Table 2. Here the total night as well as AW and S4 stages are considered. The white background of the cells indicates statistically significant correlations, the significance level being given below the table. The following observations can be made:

i) Stage AW demonstrated a strong negative correlation between f_W^h and f_W^{α} , i.e., increases of f_W^h were interrelated with decreases of f_W^{α} and vice versa. In addition, a negative correlation is obvious between $f_W^{t'}$ and f_W^p.

ii) Stage S4 showed a strong negative correlation between f_W^t and, on the other hand, $f_W^{t'}$ and f_W^{δ} .

iii) The total night record revealed a negative correlation between f_W^t and, on the other hand, $f_W^{t'}$ and f_W^{β}, which was already indicated in Fig. 2a, b. A week positive correlation was given between f_W^t and f_W^{α}.

Table 2. Cross-correlation coefficients of weighted mean frequencies f_W from HRV and EEG for awake (AW), deep sleep stage 4 (S4), and all night (AN) concerning different spectral ranges.

Spectral ranges for **EEG**	Spectral ranges for **HRV**											
	Total (f_W^t)			Humoral (f_W^h)			Sympathetic (f_W^s)			Parasympathetic (f_W^p)		
	AW*	S4*	AN**	AW*	S4*	AN**	AW*	S4*	AN**	AW*	S4*	AN**
Total ($f_W^{t'}$)	0.25	-0.72	-0.61	-0.48	0.05	-0.07	0.61	-0.23	0.03	-0.76	0.08	0.09
Delta (f_W^{δ})	0.19	-0.72	-0.49	0.06	0.12	-0.08	0.46	-0.32	-0.05	-0.45	0.07	0.07
Theta (f_W^{θ})	0.15	-0.08	-0.11	-0.37	-0.30	-0.02	0.35	-0.01	0.12	-0.19	0.10	-0.01
Alpha (f_W^{α})	-0.19	0.35	0.54	-0.72	-0.21	0.17	0.08	0.14	0.07	-0.30	-0.10	-0.37
SMR (f_W^{SMR})	-0.38	-0.15	-0.23	-0.50	0.11	-0.06	0.22	0.07	0.00	0.14	0.29	0.00
Beta (f_W^{β})	0.15	-0.10	-0.58	0.06	0.03	-0.17	0.28	-0.10	0.04	-0.09	0.36	0.29

* grey background indicates that hypothesis of no correlation accepted with > 95 %.

** grey background indicates that hypothesis of no correlation accepted with > 99 %.

For the sake of completeness, it should be mentioned that the stage S3 indicated correlations which are very similar to that from stage S4. This may be due to the fact that both stages represent deep sleep stages. The stage S2 revealed only very weak correlation coefficients (though significant), their absolute value not exceeding 0.5. The significant coefficients from the stage REM were even lower. The stage S1 showed no stationary RR-intervals (Table 1), thus no correlations were calculated here.

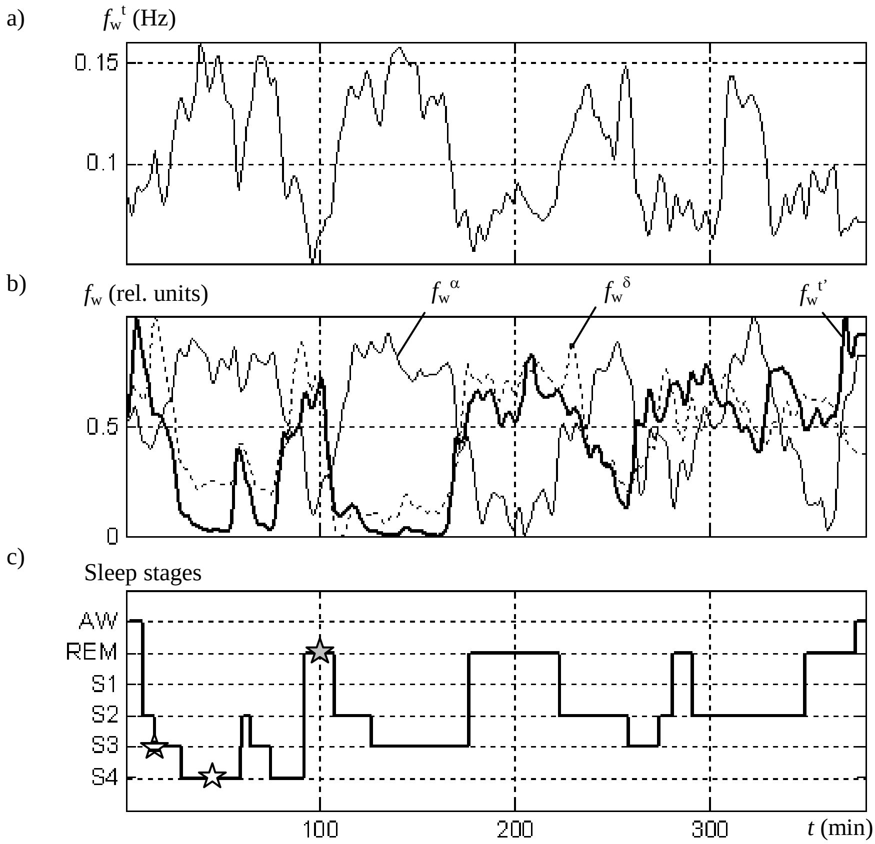

Fig. 2. Courses of spectrum-weighted mean frequencies f_W over the night. a) f_W^t of HRV concerning total spectral range. b) f_W of EEG concerning total spectral range $f_w^{t'}$, delta range f_w^δ, and alpha range f_w^α. c) The corresponding hypnogram showing sleep stages over night (AW awake, REM rapid eye movements, S1-S4 sleep stages from drowsy to deep sleep). The sterns denote time instants related to the data depicted in Fig. 1b, c

Discussion

The present case study investigates the relation of the spectrum-weighted frequencies f_W of HRV and EEG for different widely-established spectral ranges and for different sleep stages. It demonstrates numerous interrelations, the strongest inverse relation being given between f_W of the total spectral range of HRV and that of EEG. Interestingly, the latter f_W are even approximately related to the sleep profile of the study subject, i.e., they have a predictive value in identifying shallow sleep versus deep sleep.

Selected spectral ranges revealed lower correlations, which may be due to the strict (or narrow) band limits while calculating f_W in the light of non-zero values of the power spectral density p at band limits. For instance, an implication of such restriction can be observed in Fig. 1b, where maxima of p are not exactly matched by calculated f_W. Furthermore, an obvious restriction of the given study is that only data from a single subject was used. The statistical relevance of f_W, e.g., their predictive value of sleep architecture, should be verified in future using extensive data bases.

However, the present case study has demonstrated a relationship between HRV and EEG in different sleep stages suggesting a close dependence of autonomic cardiovascular control on central nervous system. The methodology of the spectrum-weighted frequencies may even help assess the quality of sleep, e.g., fraction of deep sleep stages. The sleep-related relation of HRV-measures and EEG-measures emphasizes the importance and usability of the HRV-analysis in sleep studies, since EEG is considered as a standard for sleep staging. In praxis, it may be very attractive to roughly assess the sleep architecture in a very simple and comfortable way, e.g., by using only a single ECG-signal, which is relevant for many medical areas.

References

[1] 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.

[2] **Akselrod S., Gordon D., Ubel F. A., Shanon D. C., Barger A. C., Cohen R. J.** Power spectrum analysis of heart rate fluctuations: a quantitative probe of beat-to-beat cardiovascular control // Science, 1981, 213, 220-222.

[3] **Varoneckas G.** Advanced sensoring of human physiological states using heart rate variability // Int. J. Applied Electromagnetics and Mechanics, 2007, 25, 461-467.

[4] **Sayers B. M.** Analysis of heart rate variability // Ergonomics, 1973, 16, 17-37.

[5] **Rechtschaffen A., Kales A.** A manual of standardized terminology, techniques and scoring system for sleep stages of human subjects. National Institute of Health Publications 204, US Government Printing Office, Washington DC, 1968.

[6] **Zemaityte D., Varoneckas G., Sokolov E.** Heart rhythm control during sleep // Psychophysiology, 1984, 21(3), 279-289.

[7] **Ziliukas G., Varoneckas G., Staniutė M., Podlipskyte A., Brozaitiene J.** Heart rate variability and hemodynamics changes during rehabilitation in patients after coronary artery bypass grafting // Journal of Vibroengineering, 2009, 11(3), 551-555.

[8] **Varoneckas G.** Heart rate variability in the evaluation of functional status during training Operator Functional State: The Assessment and Prediction of Human Performance Degradation in Complex Tasks. Ed. G. R. J. Hockey. NATO Science Series I: Life and Behavioural Sciences. 2003; 355: 90-106.

[9] **Clifford G. D., Azuaje F., Mc Sharry P. E.** Advanced Methods and Tools for ECG Data Analysis. Artech House, 2006.

[10] **Kaniusas E., Pfutzner H., Varoneckas G.** Rationale of human skin vibrations: Registration and diagnostic value // Journal of Vibroengineering, 2009, 11(2), 249-255.

[11] **Pop-Jordanova N., Pop-Jordanov J.** Spectrum-weighted EEG frequency ("brain-rate") as a quantitative indicator of mental arousal. Prilozi, 2005, 26(2), 35-42.