Clinical Neurophysiology 118 (2007) 2752–2764

www.elsevier.com/locate/clinph

Scale-free dynamics of the synchronization between sleep EEG power bands and the high frequency component of heart rate variability in normal men and patients with sleep apnea–hypopnea syndrome

Martine Dumont [a,*], Fabrice Jurysta [b], Jean-Pol Lanquart [b], André Noseda [d], Philippe van de Borne [c], Paul Linkowski [b]

[a] *Biological Physics Department, University of Mons-Hainaut, B 7000 Mons, Belgium*
[b] *Sleep Laboratory, Department of Psychiatry, Erasme University Hospital, Université Libre de Bruxelles, Belgium*
[c] *Department of Cardiology and Hypertension Clinic, Erasme University Hospital, Université Libre de Bruxelles, Belgium*
[d] *Department of Medicine, Pulmonary Division, CHU Brugmann, Université Libre de Bruxelles, Belgium*

Accepted 25 August 2007
Available online 18 October 2007

Abstract

Objective: To investigate the dynamics of the synchronization between heart rate variability and sleep electroencephalogram power spectra and the effect of sleep apnea–hypopnea syndrome.
Methods: Heart rate and sleep electroencephalogram signals were recorded in controls and patients with sleep apnea–hypopnea syndrome that were matched for age, gender, sleep parameters, and blood pressure. Spectral analysis was applied to electrocardiogram and electroencephalogram sleep recordings to obtain power values every 20 s. Synchronization likelihood was computed between time series of the normalized high frequency spectral component of RR-intervals and all electroencephalographic frequency bands. Detrended fluctuation analysis was applied to the synchronizations in order to qualify their dynamic behaviors.
Results: For all sleep bands, the fluctuations of the synchronization between sleep EEG and heart activity appear scale free and the scaling exponent is close to one as for $1/f$ noise. We could not detect any effect due to sleep apnea–hypopnea syndrome.
Conclusions: The synchronizations between the high frequency component of heart rate variability and all sleep power bands exhibited robust fluctuations characterized by self-similar temporal behavior of $1/f$ noise type. No effects of sleep apnea–hypopnea syndrome were observed in these synchronizations.
Significance: Sleep apnea–hypopnea syndrome does not affect the interdependence between the high frequency component of heart rate variability and all sleep power bands as measured by synchronization likelihood.

Keywords: Detrended fluctuation analysis; Heart rate variability; Sleep; Spectral analysis; Synchronization likelihood; Apnea–hypopnea syndrome

---

1. Introduction

The dynamic interdependence between heart rate variability (HRV) and sleep has met with growing interest in recent years. Indeed, a large number of cardiovascular events such as myocardial infarctions, sudden death, and stroke have an increased frequency in the early hours after waking (Muller et al., 1985, 1987; Somers et al., 1993; Hu et al., 2004).

The triggering mechanisms for these events are not clear and research efforts are focused on any changes in the course of the night that can contribute to the initiation of such phenomena.

---

* Corresponding author. Tel.: +32 65373462; fax: +32 65373537.
E-mail address: martine.dumont@umh.ac.be (M. Dumont).

1388-2457/$32.00
doi:10.1016/j.clinph.2007.08.018

Sleep is known to be a dynamic state of consciousness that is characterized by fluctuations in autonomic activity controlling coronary artery tone, systemic blood pressure, and heart rate (Vanoli et al., 1995). Heart rate variability is classically used to study fluctuations in the respective influence of sympathetic and vagal cardiac activities (Task Force, 1996).

The interdependence between HRV and sleep has been studied through investigation of the behaviors of the Low and High Frequency (LF and HF) spectral components of the HRV, associated, respectively, to the sympathetic and parasympathetic cardiac activities and the spectral power bands (δ, θ, α, σ and β) of the sleep EEG.

The spectral power bands (δ, θ, α, σ and β) are powerful tools for the quantitative study of sleep EEG architecture and its sustained physiology. The maximum of the delta power corresponds to the slow-wave sleep while the sigma power band is associated to Stage 2. The maximum of the theta and alpha powers is found in REM sleep and wake state, mostly in REM sleep for theta, and mostly in awake stage for alpha. The beta power band evolves in opposition to delta band across the first episodes of nREM sleep and its maximum is associated to wake stage (Uchida et al., 1992; Aeschbach et al., 1997; Merica and Blois, 1997; Tan et al., 2000).

To investigate the interdependence between HRV and sleep, linear methods have been mainly used such as scatter plots (Ako et al., 2003; Yang et al., 2002, 2003) and linear response formalism through computation of cross correlation coefficients (Brandenberger et al., 2001), gain, and coherence (Jurysta et al., 2003, 2005, 2006). Linear investigations concluded that although all electroencephalographic power bands are linked to normalized high frequency (Jurysta et al., 2003), modifications in cardiac vagal activity show predominantly parallel changes with the delta band (Ako et al., 2003; Jurysta et al., 2003) and precede these changes (Brandenberger et al., 2001; Jurysta et al., 2003). The delay between changes in the relatively predominant cardiac vagal activity and in delta power is maintained in middle-aged men (Jurysta et al., 2005).

In Dumont et al. (2004), we questioned the nature (linear or nonlinear) of the coupling between the different sleep EEG spectral components and the HF_{nu} band of the ECG recording in young healthy subjects. Such a question required the use of nonlinear methods.

Nonlinear methods, such as generalized synchronization or nonlinear prediction, have been mostly applied to investigate the interdependence between recordings of the same nature, such as different EEG signals for the analysis of brain activity e.g. during rest (Breakspear and Terry, 2002), cognitive tasks in Alzheimer patients (Stam et al., 2002), or epileptic seizures (Le Van Quyen et al., 1999; Arnhold et al., 1999; Altenburg et al., 2002). Interactions between different EEG electrode recordings during sleep were also investigated by nonlinear methods (Pereda et al., 2001; Ferri et al., 2005).

The interdependence between signals of different natures recorded from different physiological systems has also been treated in this way. Examples include applications to the cardiovascular (e.g. Nollo et al., 2002) and cardiorespiratory (e.g. Toledo et al., 2002) systems. Our investigations belong to this class.

In Dumont et al. (2004), we investigated the coupling between the different sleep EEG spectral components and the HF_{nu} band of the ECG recording by computation of the Synchronization Likelihood (SL) average values on the first three nREM–REM cycles. The SL is a measure of the degree of synchronization or coupling between two or more dynamic systems; it is based on the concept of the generalized synchronization and takes into account both linear and nonlinear coupling (Stam and van Dijk, 2002).

The present study represents a natural extension of the previous one; it is centered on the analysis of the dynamics of the SL characterizing the EEG/HRV interdependence during the course of the night for the detection of possible long range temporal correlation by application of Detrended Fluctuation Analysis (DFA).

DFA is a technique used to investigate the long term correlation behavior of nonstationary time series and to detect whether the investigated dynamics obey scaling or display different regimes expressed by crossover in the fluctuation behavior.

It was initially designed for the analysis of DNA nucleotide sequences (Peng et al., 1992) and heart beat time series (Peng et al., 1993, 1995). It was applied in various other fields, e.g. long-time weather records (Talkner and Weber, 2000) and economics time series (Vandewalle and Ausloos, 1997). Recently, it has been applied to global EEG synchronization (evaluated as mean SL) in eyes-closed as well as eyes-open no-task states (Stam and de Bruin, 2004) and in Alzheimer's disease (Stam et al., 2005).

The present study was designed to determine whether the synchronization likelihood and its dynamical properties could discriminate between controls and patients suffering from Sleep Apnea–Hypopnea Sydrome (SAHS) and bring insight into the understanding of this pathology.

The paper is organized as follows: Sections 2.1 and 2.2 present the samples used in this investigation and the way in which the measurements were recorded. In Sections 2.3 and 2.4, a brief recall of the synchronization likelihood and detrended fluctuation analysis methods is sketched. Section 2.5 presents the way these methods are applied to the investigation of the dynamics of the synchronizations and how the investigation of the sleep cycle effects is performed. Technical details about software and statistical analysis are given in Sections 3 and 4. The Section 5 starts with an example of typical results for one sample subject in Section 5.1. The investigation of mean synchronizations versus groups, sleep EEG band, and sleep cycles is the object of Section 5.2 while Section 5.3 is devoted to DFA results. Finally, the findings are discussed in Section 6.