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Time-varying Analysis of the Heart Rate Variability during REM and Non REM Sleep Stages

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Abstract — **Spectral decomposition of the Heart Rate Variability during whole night recordings was obtained, in order to assess the characteristic fluctuations in the heart rate and their spectral parameters during REM and NREM sleep stages. A Time-Varying Autoregressive Model was used in the analysis since it allows both real time and transitory episodes evaluation of spectral parameters of the heart rate variability and consequently an analysis of the Autonomic Nervous System behavior. Three whole nights records coming from three healthy subjects were used in the study. The results obtained during the study are in accordance with the previous ones in literature: an increment in LF power and in LF/HF ratio and a decrement in HF power when REM values are compared with NREM sleep stage. The pole of the autoregressive model in the HF range helps to separate the REM and NREM sleep epochs. When NREM is evaluated, the pole tends to be very close at unitary circle, while in REM this pole goes far from the unitary circle and its phase becomes less stable.**

Keywords— **Heart Rate Variability, Sleep Stages, Autoregressive Models, Autonomic Nervous System.**

I. Introduction

Previous studies have shown that heart rate presents a diminution during sleep phase as compared with wakefulness. This change attains typical fluctuations at the different sleep stages. During REM (Rapid Eye Movement) and NREM (Non Rapid Eye Movement) sleep stages the heart rate is lower than during relaxing wakefulness, and higher in REM when compared with NREM sleep stages. These variations in heart rate fluctuations have been explained as a depression or decreasing in the activation of the sympathetic activity during NREM and by an instability and increasing in REM [1].

Spectral analysis, in the study of the cardiovascular signals, has demonstrated to be a fine non invasive tool for evaluating the state of the Autonomic Nervous System (ANS), and it has been used in order to assess the Heart Rate Variability (HRV) changes during sleep [2-5]. These variations exhibit characteristic oscillations which corresponds to variations of parasympathetic and sympathetic branches of the ANS. Wide band of the spectral components of HRV ranges from 0.003 Hz until 0.5 Hz, where the range between 0.003–0.04 Hz (Very Low Frequency component VLF) takes account of long-term regulation mechanisms, 0.04–0.15 Hz (Low Frequency Component LF) represents sympathetic activation, and finally the range between 0.15–0.5 Hz (High Frequency Component HF) corresponds to vagal tone and it is highly influenced by respiration [6-7]. Spectral decomposition technique has shown consistent results: a vagal increase during NREM sleep stage measured by the HF component and increase of sympathetic activity measure by the LF and LF/HF ratio during REM sleep stage [5].

HRV signal is stationary in constant conditions, its first and second statistic moments through a time window of a few minutes do not change, and application of Fourier Transform or Autoregressive Batch analysis are adequate spectral decomposition techniques [8]. However, when it is necessary to analyze sequences where transitory changes in the signal could happen, such as variations during Valsalva Maneuver, tilt test or Obstructive Sleep Apnea events, these approaches don't result to be the most suitable for the analysis, because the signal acquires non-stationary characteristics. To overcome this inconvenient there are two possible ways. On one hand, techniques such as Short Time Fourier Transform, Discrete Wavelet Analysis, Time-Frequency Distributions and Time-Varying Analysis could be used. On other hand, it could be taken a short data sequences where fast changes are not present as some studies proposed, in different sleep stages [2-5].

However, time-varying autoregressive models allow to assess, on a beat to beat basis, the spectral parameters of HRV signal in a fast and efficient way independently on the transitory events found through the whole night recording (provoked by arousals, body movements, changes on sleep stages or apneas).

The aim of this work is to assess the spectral parameters by time-varying autoregressive spectral analysis of the HRV during whole night recordings, in a beat to beat basis. The study focus on the temporal evolution of LF, HF spectral powers and on the module and phase of a representative pole of the autoregressive model in HF band during REM and NREM sleep stages

II. Methodology

Three polisomnographic whole night recordings were obtained from three healthy subjects with ages between 40 and 50 years and Body Mass Index 28 ± 2 Kg/m2. Data were obtained using a polymnosographic system Heritage Digital PSG Grass Telefactor with 512 Hz as sampling frequency. Records include oxygen saturation, body position, two encephalographic derivations (C4/A1 and O1/A2), chin electromyogram, left and right electrooculograms, leg movement, airflow, thoracic and abdominal efforts and electrocardiogram. Stages 1, 2, 3, 4 and REM sleep were scored according to the standard criteria (Rechtschaffen and Kales, [9]). In the present study

only the hipnogram and the ECG signal were analyzed for sleep classificaton.

A. HRV analysis

From the ECG data, the R peaks where detected and RR intervals were measured using a built and tested algorithm. The time series were searched for misdetections and ectopic beats were corrected. The time-variant spectra was estimated by an autoregressive model at each RR interval. A model order of 8 was selected for the whole night records for all subjects. Model order selection criteria was the minimum number of coefficients that could fit the HRV signal in order to simplify the analysis and the attempt to have only one pole in each relevant spectral band. The recursive least square algorithm (RLS) was used to estimate autoregressive parameters updating. The forgetting factor $\lambda = 0.98$ was chosen across all the subjects' records. This means that the exponential decay of the algorithm has a time constant of about 50 samples [10].

The power spectrum was computed from the estimated time-varying autoregressive parameters for each time series [10]. From each spectral estimation we computed the time variant spectral indexes of HRV: total power (TP); LF power (in the range 0.02 – 0.15 Hz); HF power (in the range 0.15 – 0.6 Hz); and low to high frequency ratio (LF/HF). Likewise, the module and phase of the representative pole in the HF band was calculated at each beat from the autoregressive coefficient vector.

B. Data Analysis

The mean values of RR intervals, spectral parameters, module and phase of the representative high frequency pole, were computed on consecutive time windows of 30 seconds, across all night in order to rescale the data to the same time scale used for the classical evaluation of the hypnogram.

TABLE I. Mean and SE of the HRV indexes in function of REM and NREM sleep stages.

Indexes	**Sleep Stage**	
	NREM	REM
RR (s)	1.136 ± 0.0247 *	1.0484 ± 0.0363 *
LF ($s^{\wedge 2}$)	0.1437 ± 0.0689 *	0.4698 ± 0.163 *
HF ($s^{\wedge 2}$)	0.3158 ± 0.0829	0.2989 ± 0.1048
LF/HF	0.6864 ± 0.3024 *	1.8681 ± 0.6037 *
|HF Pole|	0.9269 ± 0.0128 *	0.8484 ± 0.0177 *
Ang (HF Pole)	0.3563 ± 0.0218	0.3467 ± 0.0247

RR = time interval between consecutive R peaks of the Electrocardiogram, LF = low frequency power, HF = high frequency power, LF/HF low to high frequency power ratio, |HF Pole| = module of the higher pole in the HF band, Ang (HF Pole) = angle of the higher pole in the HF band expressedin Hz. * represent significant differences $p < 0.05$.
HF band, Ang (HF Pole) = angle of the higher pole in the HF band. * represent significant differences $P < 0.05$.

Therefore, intervals of data according to the following rules were selected with the purpose of comparing the REM and NREM sleep effects on HRV parameters:

a) Spectral parameters were taken one or two epochs after and previously to the beginning and ending epoch of the REM stage respectively.

b) NREM stages were 2 (light sleep), 3 and 4 (deep sleep) with at least 10 consecutive epochs. It is important to mention, that mixed intervals (containing sleep stages 2, 3 and 4) were selected only if there was a sleep phase change from 2 to 4 and not in apposite direction.

Two groups T-test was performed to evaluate significant statistical differences ($p < 0.05$) between REM and NREM sleep stages in each parameter.

III. RESULTS

Whole night data coming from three healthy sleepers were analyzed. A total of 736 and 456 epochs of NREM and REM respectively were included in the analysis. Table I presents mean values and standard error (SE) of the HRV indexes of REM and NREM sleep stages through all night. RR intervals, HF pole module, HF pole angle and HF power showed a decrement when REM is compared to NREM sleep stage, but significant differences were present only in RR intervals and HF pole module. Contrarily, LF component and LF/HF ratio had a significant increment from NREM to REM stages.

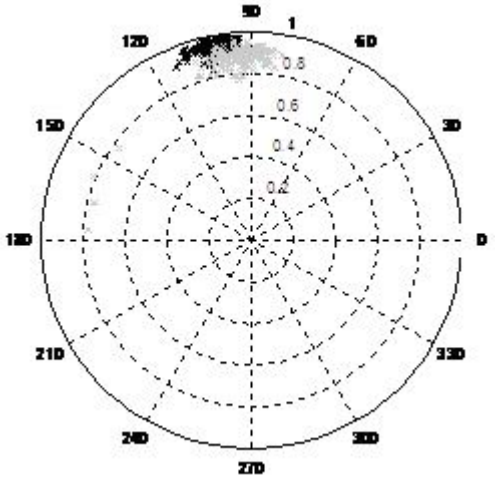

Fig 1. Example of HF pole displacement of a subject during REM and NREM sleep stages. Black 'x' represents NREM while gray 'x' REM sleep stage. 180 in the unity circle correspond to half the sampling frequency (1/[mean of the RR intervals of all night]).

Fig. 1 depicts the placement of the representative HF pole during REM (gray 'x') and NREM (black 'x') sleep stages for a healthy sleeper subject. During NREM stage the HF poles are concentrated very close to the unitary circle, and these ones go far from the unitary circle and move towards a lower frequency during REM. In the figure 180

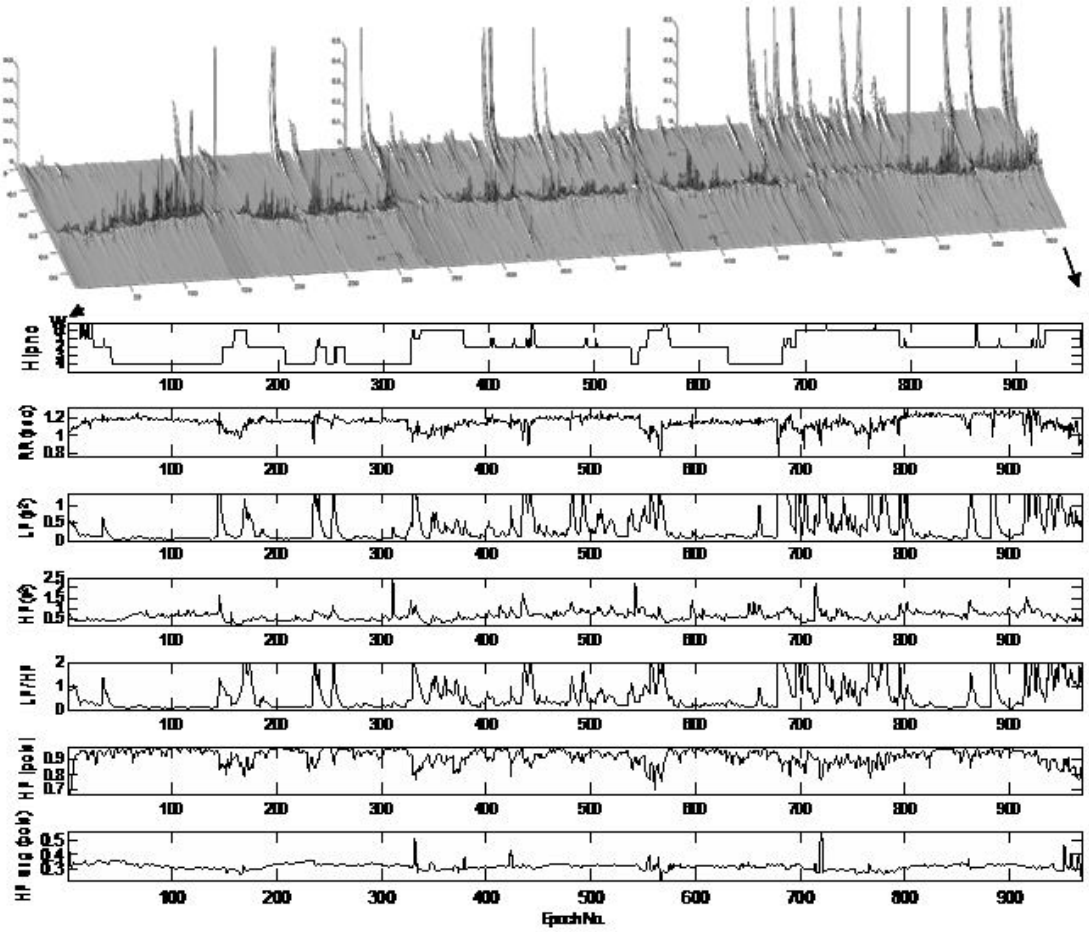

Fig 2. Example of the whole night epoch evolution of a) spectral power and b) spectral indexes of the heart rate variability. RR = time interval between consecutive R peaks of the Electrocardiogram, LF = low frequency component, HF = high frequency component, LF/HF low to high frequency ratio, |HF Pole| = module of the higher pole in the HF band, Ang (HF Pole) = angle of the higher pole in the HF band. All Indexes are presented as the mean of 30 seconds at each epoch, which is the time of the hipnogram epoch.

represents the half of the sampling frequency (1/[mean of the whole night RR intervals]).

Fig. 2 shows an example of the time evolution of PSDs and spectral indexes of the HRV during all night of one subject.

From the PDS epoch evolution it can be noticed a clear amplitude decrement hence as a displacement toward a lower frequency of HF in correspondence to the REM stages (visible on the hypnogram plotted below), together with a high LF increment. Spectral indexes plot shows RR intervals, LF and HF power, LF/HF, module and frequency of HF pole during each epoch.

Values of the indexes at each epoch were obtained by computing the mean each 30 seconds which corresponds to the classical time scaling used in the evaluation of the clinical hypnogram. From the RR plot one can appreciate a decrement when a REM stage occur or during a change from a deeper to a lighter sleep stage, for instance, the change of stage from 4 to 2. HF showed similar variations, but not so clear, and LF behavior presented the opposite variations to the RR intervals, however with strong changes. Observing the LF/HF ratio, the combination of powers in both the relevant frequency ranges, it is remarkable a clear difference between the REM and NREM sleep stages. Furthermore, the changes in sleep stage and awakenings are very clear in this index. The module of the HF pole shows a characteristic oscillatory pattern. During the REM phase this tends to decrement as compared with NREM one. The last subplot puts into evidence the frequency of the HF pole, where an instability of the angle pole takes place during REM stage and almost constant position is maintained in NREM phase.

IV. Discussion

Spectral analysis of the Heart Rate Variability of three healthy sleepers was presented. Whole night recordings were used in order to evaluate influences of REM and NREM sleep phases onto HRV spectral indexes obtained by an Autoregressive model. Our main observations are: 1) autoregressive time-varying analysis results to be an adequate and fine tool to evaluate the behavior of the ANS

through whole night recordings; 2) the representative pole in HF could be a new parameter when REM and NREM sleep stages need to be discriminated; 3) our results are in agreement with most of the studies presented previously [2-5]. There was an increment in the heart rate, LF component, LF/HF ratio and decrement in the HF component when REM sleep phase is compared with respect to NREM one. It is important to remark this point, because the AR model allows to evaluate the HRV parameters during all night without the necessity of search short sequences of stationary data for the evaluation, but it is done automatically. This approach allows the assessment of the ANS on a beat-to-beat basis through whole night data, which can, in a post analysis, be used for evaluating different slots of data, for instance, sequences of 2, 5 or 30 seconds. It is clear that the approach used in the present study is completely dependent on the RR intervals. This means, that the RR sequence has to be evaluated with particular attention. However solution to this problem could be given by taking some considerations in the algorithm. Differences between sleep stages 4 and 2 were out of this study. Such a discrimination will be considered in the future. Population used for the study is very small and insufficient, by the statistical viewpoint, but enough to give a new line of research inside to the sleep medicine. Another criticism to the study is concerned to the model order and forgetting factor. On one hand, we decided to use a minimum order (8 coefficients) with the idea to obtain at least one pole in each spectrum band. Possibly it is not the best model order which fits the HRV signal in all the different situations found in a whole night record. In the present work we choose the minimal order able to represent all the relevant spectral components when they are present in the PSD. On other hand, the selection of $\lambda = 0.98$ as forgetting factor allows to follow also the typical transitory produced by different episodes, such as Arousal from sleep, apneas and so on, and seems to be the correct value for correct sleep analysis.

V. Conclusion

The time-varying Autoregressive analysis resulted a fine tool to assess the cardiovascular parameters during a whole night recordings. Results obtained using this approach are in agreement with previous studies.

During REM as compared with NREM sleep stage, LF power, RR intervals, LF/HF presented a noticeable increment, while HF showed a reduction. The pole module of HF component is closer to the unitary circle during NREM and far from it during REM. Future work will consist in incrementing the number of subjects and in the discrimination between sleep stage 2 and 4.

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