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Respiratory-cycle related analysis of the EEG-spectrum during sleep: A healthy population study

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Abstract— **Recent research has shown the EEG's spectral changes that occur in synchrony with the respiratory-cycle. During wakefulness, and for healthy subjects it is reported that the EEG power in several frequency bands changes between the expiratory and inspiratory phases. For sleep-disordered breathing (SDB) patients, it is reported that the amplitude of changes in normalized EEG power (referred to as respiratory-cycle related EEG changes RCREC) within a respiratory-cycle decreases after a successful intervention to alleviate the SDB condition.**

In this paper, we focus on analyzing the changes in the sleep's EEG spectrum related to the respiratory-cycle for a healthy population comprising 39 subjects. For 3 sleep stages (N2, N3, REM), 6 EEG channels, and 7 frequency bands, two types of EEG spectral analyzes were considered: 1) the ratio between the EEG power during expiration and that during inspiration, and 2) the RCREC.

For the first type of analysis and at the population level, no statistically significant difference was found between the EEG power during expiration and that during inspiration. For the second type of analysis, the RCREC for all conditions is at a level that is statistically significantly larger than 0.1. The latter being the value at which the RCREC decreased after successful SDB intervention.

I. Introduction

The influence of the respiratory-cycle on the human Electroencephalogram (EEG)-spectrum during various types of breathing was described in [1] . In this study conducted on healthy subjects, spontaneous and paced breathing (at 0.1, 0.25, and 0.5 Hz) were considered. The EEG was analyzed in the typical frequency bands: δ (0.5-4 Hz), θ (4-8 Hz), α (8-12 Hz), and β (12-30 Hz). Various statistically significant differences between the power during inspiration and that during expiration were observed including, 1) the δ-power and total power during inspiration are higher in anterior-temporal regions during spontaneous and 0.1Hz-paced breathing, 2) the theta power during expiration is higher in most regions during 0.5Hz paced-breathing, and 3) the delta power in the parietal region during expiration is higher for 0.25Hz paced breathing.

During sleep, the so-called respiratory-cycle EEG related changes (RCREC) are used in [2], [3], [4] to characterize micro-arousals in the context of sleep disordered breathing (SDB). The RCREC for a given frequency band is estimated as follows. The nasal airflow signal is used to detect the expiration and inspiration periods within each respiratory-cycle. Both periods are in turn subdivided into two which results in four periods: 1) early expiration, 2) late expiration, 3) early inspiration, and 4) late inspiration. The EEG power in the considered frequency band is then estimated for each segment. A normalized power for each segment is then obtained through dividing it by the average power within a respiratory-cycle and subtracting one from such ratio. The RCREC is defined as the maximum absolute difference between the normalized powers corresponding to any pair of segments. In [2], RCREC in the δ, θ, and σ (13-15 Hz) bands diminish after surgical intervention for SDB. In [3], σ-RCREC is positively correlated with diurnal sleepiness in SDB patients. In addition, [4] reports that δ, θ, α, σ, and β-RCREC tend to diminish acutely with alleviation of upper airway obstruction by positive airway pressure (PAP) [5].

In [1], respiratory-cycle EEG changes during wakefulness in a healthy population are described while [2], [3], [4] focus on sleep disorder breathing. This paper aims at analyzing the influence of the respiratory effort on the sleep EEG-spectrum in various frequency bands depending on the sleep stage and for a healthy population.

This paper is organized as follows. Section II describes this study's dataset and the signal processing methods. The results and discussion are presented in Section III. The conclusions are presented in Section IV.

II. Methods

A. Dataset

The dataset used in this study consists of the polysomnography (PSG) recordings of healthy subjects (one night per subject) from the SIESTA database [6]. Out of the 200 recording from healthy subjects in SIESTA, 100 were randomly pre-selected. For each of these recordings the automated detection of respiratory-cycles (described in Section II-B) in the respiratory flow signals was tested, and the results were visually inspected. The 39 recordings for which at least 95% accuracy was achieved were selected for this study.

The PSG includes: i) 6 EEG channels with mastoid (M1, M2) as reference: (Fp1-M2, Fp2-M1, C3-M2, C4-M1, O1-M2, and O2-M1), ii) electro-oculogram channels, iii) submental electromyography, iv) electrocardiogram, and v) respiratory signals (airflow and movements of the chest wall and abdomen). The sampling frequency for the signals was of at least 100 Hz [6]. The results of visual sleep scoring performed by sleep experts are available for each recording.

As suggested in [2], the airflow signal is used to analyze the respiration cycles for each subject. The influence of

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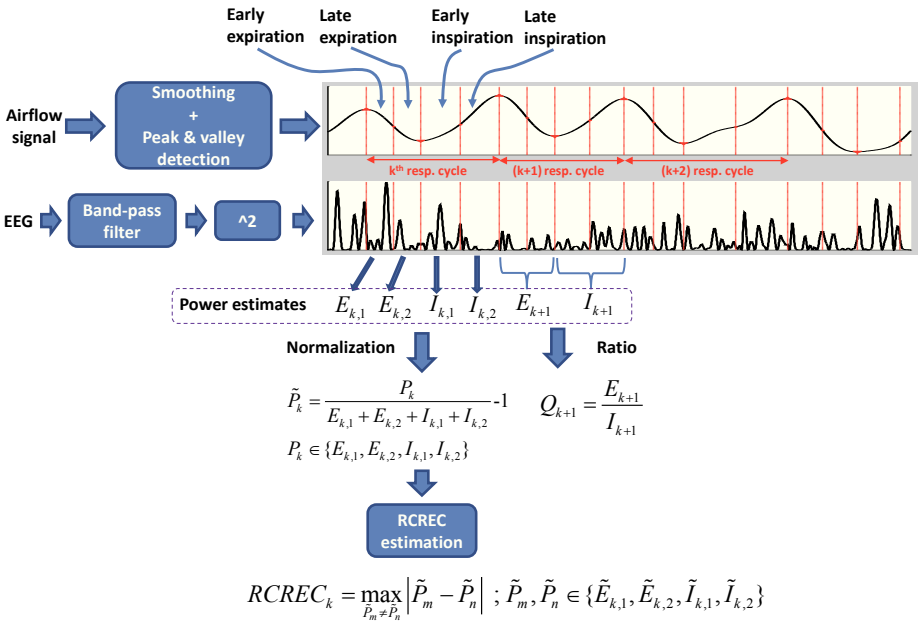

Fig. 1. Signal processing methods.

the respiratory-cycle on the EEG is assessed for each EEG channel and sleep stage.

B. Signal Processing

The signal processing methods are summarized in the diagram of Figure 1. The EEG is first band-pass filtered in the targeted frequency-band. The resulting signal is then squared in order to obtain the instantaneous EEG energy in that band. EEG Power estimates are computed by averaging the instantaneous energy over specific time periods that are determined from the airflow signal. Figure 1 illustrates this process for a single EEG channel. This process is identical for each EEG channel.

The frequency bands for the EEG signal considered in this study are: δ (0.5-4 Hz), θ (4-8 Hz), α (8-12 Hz), σ (13-15 Hz), β (15-30 Hz), γ (30-49 Hz), and 0.5-49 Hz. The power in the latter band is referred to as *total-power*.

The airflow signal is processed in order to detect its peaks and valleys which are used to define the respiratory-cycles. Because the respiratory signal is a comparatively slow signal, a band-pass filter (in the band from 0.05 to 0.5 Hz) is initially applied. The resulting signal is then smoothed using a second-order Savitzky-Golay Least-Squares Polynomial Filter [7]. A local peak (valley) is defined as a data sample that is larger (smaller) than its neighboring samples. To avoid false detections, it is imposed that two consecutive peaks (valleys) should be separated by at least one second. A respiratory-cycle is defined between two consecutive peaks and includes a valley in between. The time between the first peak and the valley corresponds to the expiration period and the time between the valley and the second peak corresponds to the inspiration period (this is illustrated in Figure 1 top).

Using the respiratory-cycles as reference, two types of EEG spectral analyzes are considered: 1) the power ratio between expiration and inspiration similarly to [1], and 2) the RCREC as defined in [2], [3], [4].

1) Power ratio Expiration/Inspiration: For a given respiratory-cycle and particular frequency band, the EEG power associated with the expiration is estimated by 1) taking the average, over the expiration period, of the EEG energy in the frequency band of interest, and 2) dividing such average by the duration in seconds of the expiration period. The EEG power corresponding to the k-th respiratory-cycle's expiration is referred to in Figure 1 as E_k. The EEG power associated with the inspiration (referred to as I_k) is estimated in a similar manner as for the expiration. The ratio of the expiration to inspiration is referred to as $Q_k = E_k/I_k$. For ease of presentation, the frequency band variable was omitted in the notations E_k, I_k, and Q_k.

2) RCREC: Estimating the RCREC according to [2] requires that both expiration and inspiration periods are each subdivided into two equally long subperiods. This results into four subperiods: early expiration, late expiration, early inspiration, and late inspiration (see Figure 1). Thus, the first (last) two have equal duration. For a given frequency band, the EEG power in any sub-period is obtained by taking the average of the instantaneous EEG energy in the band and dividing by the sub-period's duration.

The EEG power values for the sub-periods of the k-th respiratory-cycle are referred to as (see Figure 1) $E_{k,1}, E_{k,2}, I_{k,1}$, and $I_{k,2}$ for the early expiration, late expiration, early inspiration, and late inspiration respectively. Each

TABLE I

SPAN OF THE DURATION OF RESPIRATORY-CYCLES FOR EACH SLEEP STAGE.

	N2	N3	R
Duration span[s]	3.26-6.42	3.28-5.78	2.84-7.37
Breathing rhythm [Hz]	0.15-0.31	0.17-0.30	0.14-0.35

of these power values is further normalized through dividing it by the power in the whole respiratory-cycle, i.e. the sum: $E_{k,1} + E_{k,2} + I_{k,1} + I_{k,2}$ and subtracting one from that ratio (1).

$$\tilde{P}_k = \frac{P_k}{E_{k,1} + E_{k,2} + I_{k,1} + I_{k,2}} - 1, \quad (1)$$

where $P_k \in \{E_{k,1}, E_{k,2}, I_{k,1}, I_{k,2}\}$ and $\tilde{P}_k \in \{\tilde{E}_{k,1}, \tilde{E}_{k,2}, \tilde{I}_{k,1}, \tilde{I}_{k,2}\}$.

The RCREC of the k-th respiratory-cycle is defined [2] as the maximum of the absolute value of the difference between any pair of normalized power values in the cycle. This can be written as follows.

$$RCREC_k = \max_{\tilde{P}_m \neq \tilde{P}_n} |\tilde{P}_m - \tilde{P}_n|, \quad (2)$$

where $\tilde{P}_m, \tilde{P}_n \in \{\tilde{E}_{k,1}, \tilde{E}_{k,2}, \tilde{I}_{k,1}, \tilde{I}_{k,2}\}$.

III. RESULTS AND DISCUSSION

The respiratory cycles of sleep stages N2, N3, and REM (R) were considered in this study. The sleep stage N1 was omitted from the analysis because of its brevity. The span of the duration of the respiratory-cycles for each sleep stage and across this study's population is reported in Table I.

A. Power Ratio Expiration/Inspiration

For each subject in the study, the power ratio expiration/inspiration (estimated as in Section II-B) was obtained for each sleep stage, EEG channel, frequency band, and respiratory-cycle.

The logarithm of the ratio (*log-ratio*) was then used to determine statistical significance. The null hypothesis that the log-ratio data (for a given subject, sleep stage, EEG channel, and frequency band) comes from a continuous symmetric distribution with zero median (i.e. the ratio is not different from 1) was tested using a non-parametric Wilcoxon two-sided signed-rank test [8]. A significance level of 0.05 was considered which after correction for multiple comparisons [9] (3 sleep stages $\times$ 6 EEG channels $\times$ 7 frequency bands = 126) was scaled to 0.05/126=3.97e-4.

The number of subjects for whom statistical significance was reached is shown in Figure 2 for each sleep stage, EEG channel, and frequency band. In most cases, statistical significance appears for ≤ 1 subject. In 4 subjects (10% of the population in this study), the EEG power in the gamma band during expiration is significantly different (lower) from that during inspiration for fronto-polar electrodes and sleep stages

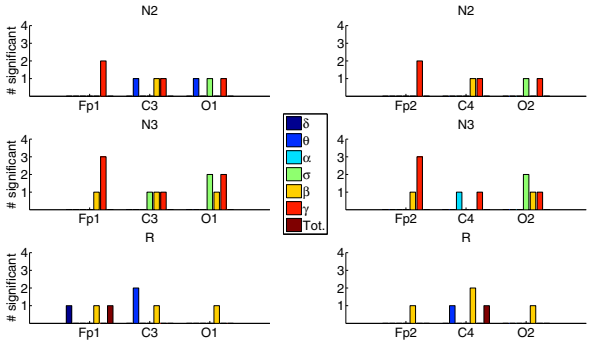

Fig. 2. Number of subjects for whom the Expiration/Inspiration ratio is significantly different from 1.

N2 and REM. However, tests for statistical significance over the 39 subjects considered in this study resulted in 0 cases (sleep stage, EEG channel, frequency band) where the EEG power during expiration was significantly different from that during inspiration.

Expiration/inspiration EEG power differences occur in a rather small percentage of the total number of subjects observed here. This contrast with [1] where various significant results were found during wakefulness. This discrepancy can be explained by the fact that during sleep the respiratory rhythm is not as constant (see Table I) as in the experimental conditions reported in [1]. In addition, strict statistical correction for multiple comparisons was used in this paper.

B. RCREC

The average RCREC across subjects for all sleep stages, electrodes, and frequency bands is shown in Figure 3. In [2], the RCREC value after surgical intervention for SDB decreased to less than 0.1 for frequency bands δ, θ, α, σ, and β. In [4], the median RCREC after positive airway pressure treatment for sleep apnea decreased to values below 0.1 for δ, θ, α, σ, and β. Thus, RCREC=0.1 is used as reference to test the RCREC statistics.

The null hypothesis that the RCREC (for a given sleep stage, EEG channel, and frequency band) comes from a continuous symmetric distribution with median larger or equal to 0.1 was tested using a non-parametric Wilcoxon single-sided signed-rank test [8]. A significance level of 0.05 was considered which after correction for multiple comparisons [9] (3 sleep stages $\times$ 6 EEG channels $\times$ 7 frequency bands = 126) was scaled to 0.05/126=3.97e-4. The null hypothesis was failed to be rejected for all pair combinations sleep stage, EEG channel. Thus, while in a patient population the RCREC decreases below 0.1 after SDB intervention, it is not the case that RCRECs for a healthy population are below 0.1.

This difference with the results in [4] can be explained by the fact that the population considered in this study is composed of healthy subjects. This also suggests that RCREC cannot be used as an absolute reference for sleep disordered breathing but rather as a basis for within-subject

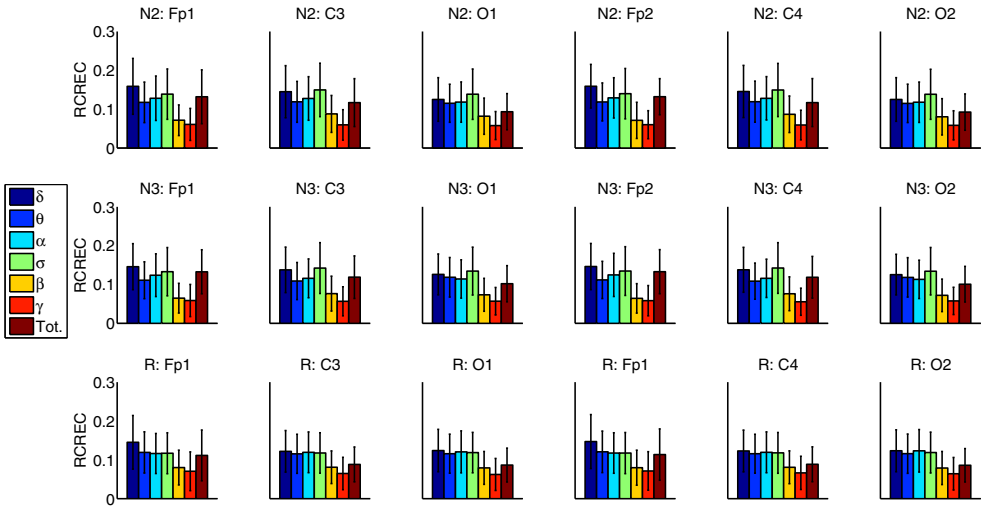

Fig. 3. Average RCREC across subjects for each sleep stage, EEG channel, frequency band, and respiratory-cycle period. The error bars correspond to the standard deviation.

comparisons where changes in the RCREC are assessed following some kind of intervention.

IV. Conclusions

The statistical analysis of the ratio: EEG power during expiration to the EEG power during inspiration on a per subject basis resulted in a rather small number of subjects for whom this ratio is sufficiently different from 1. In 4 out of the 39 subjects, the EEG power in the gamma band during expiration is significantly different from that during inspiration for fronto-polar electrodes and sleep stages N2 and REM. This result contrasts with [1] where various significant results were found during wakefulness. This discrepancy may be due to the fact that during sleep the respiratory rhythm is not as constant (see Table I) as it was in the experimental conditions reported in [1].

For the RCREC analysis, the reference value 0.1 was considered taking into account published research where RCREC decreased to below 0.1 after interventions for SDB. After statistical testing of the RCRECs obtained in this study for all sleep stages, EEG channels, and frequency bands, it was not possible to reject the null hypothesis "RCREC $\geq$ 0.1". Thus, the RCREC is not necessarily lower than 0.1 for a healthy population. This also suggests that RCREC is more suitable to be used as a within-subject index whose decrease can characterize the improvement after an intervention to alleviate SDB.

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