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Correlation of Sleep EEG Frequency Bands and Heart Rate Variability

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Abstract— **Sleep apnoea is a sleep breathing disorder which causes changes in cardiac and neuronal activity and discontinuities in sleep pattern when observed via electrocardiogram (ECG) and electroencephalogram (EEG). This paper presents a pilot study result of assessing the correlation between EEG frequency bands and ECG Heart Rate Variability (HRV) in normal and sleep apnoea human clinical patients at different sleep stages. In sleep apnoea patients, the results have shown that EEG delta, sigma and beta bands exhibited a strong correlation with cardiac HRV parameters at different sleep stages.**

I. Introduction

In the recent years, a non-invasive technique has been conducted to assess the heart and brain electrical signals as a marker of certain health problems and sleep disorders. Sleep apnoea is one type of sleep disorder which causes cessation of breathing during sleep and disruption in sleep quality. It has been established that sleep apnoea causes alterations in the brain and heart electrical activity [1-5]. Currently, an overnight polysomnographic (PSG) sleep test is accepted as a gold standard of diagnosing sleep apnoea. As the interpretation of PSG data is mainly conducted by a sleep physician or technician, the diagnosis is typically subjective. Therefore, our research focus is to find an alternative method which would minimize the parameters used in diagnosing sleep apnoea.

The HRV parameters derived from frequency domain analysis of ECG R-R Intervals (RRI), have been used to assess an Autonomic Nervous System (ANS) which plays an important role in controlling of cardiac activity like the heart rate and rhythm. The Low Frequency (LF) and High Frequency (HF) bands are used to reflect the activation of ANS subsystem; sympathetic and parasympathetic respectively. Whereas, the Very Low Frequency (VLF) band is believed to reflect the thermoregulation mechanism. The LF and HF ratio (LF/HF) is normally used as the marker of sympathovagal balances [5]. Previous studies [6-9] have suggested that HRV varies with sleep stages; the LF component dominant during Wake and gradually decreases in Non-Rapid Eye Movement (NREM) and peaks again in Rapid Eye Movement (REM). An opposite trend was reported for the HF component. Furthermore, to assess changes in the EEG activity during sleep, the spectral analysis of EEG bands is typically analysed. Few studies have investigated the relationship between specific EEG frequency bands with the HRV parameters in normal and sleep apnoea subjects [10-13]. Therefore, the aim of this pilot study was to observe the correlation between all EEG sleep frequency bands and HRV activity in normal and sleep apnoea patients at different sleep stages. The parameters obtained from this correlation can be used to distinguish from healthy patients and sleep apnoea sufferers.

II. Materials and Methods

A. Subject

Eight healthy (5 men and 3 women) and eleven sleep apnoea patients (9 men and 2 women) were recruited for an overnight study at St. Lukes Hospital (Sydney, NSW, Australia). The descriptive clinical features and sleep parameters of healthy and sleep disorder patients are presented in Table I.

B. Experimental Protocol

The 8-hour clinical sleep PSG tests were recorded with sampling frequency of 256 Hz using Bio-Logic System and Adults Sleepscan Vision Analysis (Bio-Logic Corp, USA). EEG signals were recorded using a standard 10-20 system. The surface electrodes were placed on the scalp locations C3, C4 and O2 and referenced to bridge the left and right mastoid. The ECG signal was recorded using lead II across the chest area. The other recorded PSG signals included the two electrooculograpy (EOG) channels, electromyography (EMG) electrodes, nasal and oral airflow, snoring sound, breathing effort (measured at the chest and abdomen), oxymetry, actigraphy recording body positioning and leg movements. The sleep stages were visually scored by the sleep technician at 30 s intervals according to Rechtschaffen

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and Kales criteria [14]. The respiratory signals of apnoea and hypopnoea events (AHI) were evaluated using American Academy of Sleep Medicine (AASM) Criteria [15].

TABLE I
SUBJECT CLINICAL FEATURES AND SLEEP SCORING PARAMETERS.

	Healthy	Sleep Apnoea
Age (years)	48.13 ± 10.52	50.64 ± 11.39
BMI (kg/m^2)	27.01 ± 2.94	32.92 ± 5.30
AHI	2.75 ± 1.22	48.97 ± 27.52
Total sleep time (min)	379.83 ± 59.57	393.83 ± 33.01
Sleep latency (min)	26.45 ± 30.59	23.25 ± 23.89
REM latency (min)	211.36 ± 89.81	161.52 ± 39.13
Sleep efficiency (%)	82.70 ± 8.03	87.89 ± 8.31
Wake (%)	16.35 ± 8.31	11.32 ± 8.21
Stage 1 (%)	7.5 ± 6.10	6.47 ± 3.34
Stage 2 (%)	45.83 ± 5.42	52.57 ± 11.22
Stage 3 (%)	12.51 ± 3.32	10.30 ± 7.82
Stage 4 (%)	1.84 ± 3.61	2.52 ± 4.36
REM (%)	15.01 ± 7.48	16.03 ± 5.03

III. SIGNAL PROCESSING

The EEG and ECG data was processed and analysed using Matlab software (Mathworks, USA).

A. *ECG Heart Rate Variability*

A 5-min ECG data window of free movement artefacts for each sleep stages was visually selected for the HRV analysis for each patient. Signal processing algorithm was implemented in Matlab to identify a QRS complex for extraction of RRI, based on Hilbert transformation [16]. The RRI was re-sampled at 4 Hz using Berger algorithm [17]. Further non-parametric spectral analysis based on Fast Fourier Transform (FFT) (no windowing) was performed according to Task Force [5]. The absolute and normalized spectral power within each frequency band was computed using trapezoidal integration of the area under spectral curve. The HRV frequency bands were as follows: Very Low Frequency (VLF: ≤ 0.04 Hz), Low Frequency (LF: 0.04-0.15 Hz) and High Frequency (HF: 0.15-0.4 Hz). The normalized value was calculated as LFnu=LF/(Total power – VLF) and HFnu= HF/(Total power – VLF).

B. *EEG frequency bands*

For the present analysis, C3-A2 location was utilized mainly due to our previous study results which have shown significant changes in the EEG activity in the sleep apnoea patient [2]. The power spectral of 10x30s epochs for 5-min segment was computed using FFT, no windowing function was applied with 1024 points. The estimated powers were grouped into five frequency bands: delta (0.5-4.5 Hz), theta (5-8.5 Hz), alpha (9-12.5 Hz), sigma (13-16.5 Hz) and beta (17-30 Hz). Initially, an absolute power was computed followed by the relative power which was derived by dividing the power within each band by the total power (0.5-30 Hz). For further analysis, the relative powers were averaged every 5-min.

C. *Statistical Analysis*

The Mann-Whitney, a non-parametric test was used to assess the significant differences of HRV and EEG frequency-band parameters with sleep stages between the healthy and sleep apnoea patients. To study the relationship between HRV and EEG frequency bands in different sleep stages, Pearson's correlation was applied in both groups. An alpha level of 0.05 was used for statistical test using SPSS 17 (SPSS Inc., USA) tool.

IV. RESULTS

In the healthy patient group, the LFnu and LF/HF ratio continuously decreased from Wake to Stage 4 and peaked during REM while HFnu had the converse effect (Fig.1). In the sleep apnoea group, the LFnu was higher than the healthy group during Stage 3 ($z=-3.11$, $p=0.002$). Despite the fact that the sleep apnoea group had similar trends in HFnu component, its activity was slightly lower during Stage 3 ($z=-2.42$, $p=0.016$). The sleep apnoea group also revealed a higher LF/HF activity during Stage 2 ($z=-2.13$, $p=0.033$) and Stage 3 ($z=-2.93$, $p=0.003$) in comparison to the healthy group (Fig.2). Fig.2 showed that only delta EEG increased from Wake to Stage 4 and decreased in REM. Other EEG frequency bands indicated an increase from Wake to Stage 1 and further decrease in deeper sleep and increase again in REM sleep. In sleep apnoea group, the relative power of theta EEG was lower compared to the healthy group during Wake ($z=1.98$, $p=0.048$), Stage 2 ($z=-2.63$, $p=0.008$) and Stage 4 ($z=-2.15$, $p=0.032$). In addition to Stage 2 ($z=-4.19$, $p<0.001$), alpha EEG of sleep apnoea group has also shown a lower value in Stage 3 ($z=-4.26$, $p<0.001$). Likewise, the difference of relative power in sigma EEG for the sleep apnoea and the healthy groups was observed in Wake ($z=-2.22$, $p=0.026$), Stage 2 ($z=-5.13$, $p<0.001$) and Stage 3 ($z=-2.37$, $p=0.018$). Conversely, the relative power of beta EEG in the sleep apnoea group was higher than the healthy group during Stage 3 and Stage 4 and lower during Stage 2 ($z=-2.95$, $p=0.003$) and REM ($z=-2.58$, $p=0.01$).

A. *Correlation of EEG and HRV frequency bands*

The relation between the five frequency bands of EEG and the ECG HRV parameters in each sleep stage for both groups is summarised in Table II. In the healthy group, delta EEG negatively correlated with LF/HF and LFnu during sleep Stage 3, 4 and REM; and positively correlated with HFnu in Stage 3 and 4. In contrast, the LF/HF, LFnu and HFnu in sleep apnoea group correlated with delta EEG only in Stage 3, revealing an inverse effect of healthy group. Theta EEG only correlated with LFnu (Stage 1) in the healthy group and with HFnu (Stage 1-2) in the sleep apnoea group. Correlation between HRV parameters and alpha EEG was not present in the sleep apnoea group. However, it was only correlated with LFnu for the healthy group. Interestingly, for sleep apnoea group, sigma and beta EEG showed positive correlation with HFnu; negative correlation in LF/HF; and negative correlation in LFnu both in Stage 2 and REM. Similar correlation trends for sigma and beta EEG bands were observed only with LFnu and HFnu in the healthy group.

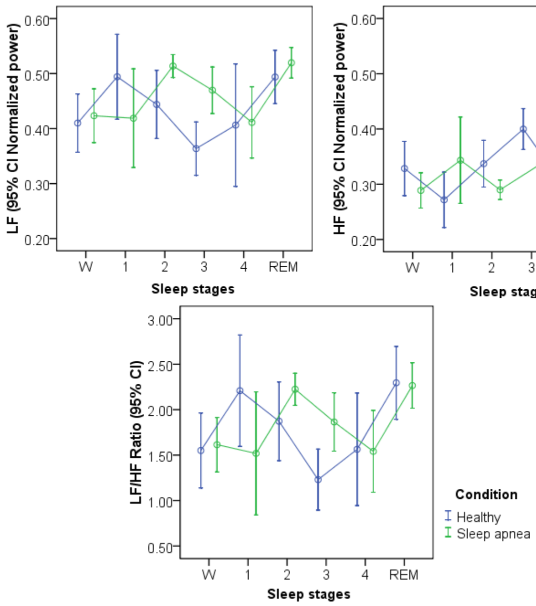

Fig 1. Mean and 95 % confidence intervals (CI) normalised power of low frequency (LF), high frequency HF and the ratio between LF and HF of HRV versus sleep stages in healthy and sleep apnoea patients.

A post hoc analysis with Bonferroni alpha rate correction of $p<0.002$ revealed that in the healthy group, only delta EEG was negatively correlated with LF/HF during Stage 4 whereas a positive correlation was observed in the sleep apnoea group. Sigma and beta EEG also showed a significant difference for LF/HF and LFnu during Stage 2 and REM respectively in the sleep apnoea group.

V. Discussion and Conclusion

Results from this pilot study confirmed the existence of association between the HRV parameters and delta EEG frequency band in normal subject which varied with sleep stages as reported in previous studies [9-12]. Our results have shown that in normal group, delta EEG which often prevails in deep sleep was inversely correlated with LFnu and LF/HF and positively correlated with HFnu suggesting a decrease in sympathetic activity and an increase in parasympathetic activity. Our pilot study also revealed an increase in LFnu and LF/HF particularly during Stage 2 in sleep apnoea patients compared with the healthy patients. Our findings coincide with the results reported by Dingli and Jurysta [3, 4] which revealed an increase in sympathetic and parasympathetic activity around apnoea episodes which occurred mostly during NREM sleep. As reported by Svanborg [18], the changes in delta activity were increased during NREM in sleep apnoea patients. Our results revealed that delta EEG and LFnu positively correlated, observed in sleep apnoea group during Stage 3. In addition, beta and sigma also showed a negative association with the LFnu and LF/HF parameters. This association observed during Stage 2 and REM was perhaps due to predominance of cardiac sympathetic during apnoea episodes.

In conclusion, our study elucidated a significant correlation between cardiac activity and EEG frequency bands particularly in delta, beta and sigma in sleep apnoea group. Further studies using non-linear methods for EEG and ECG feature extraction is required to verify this association.

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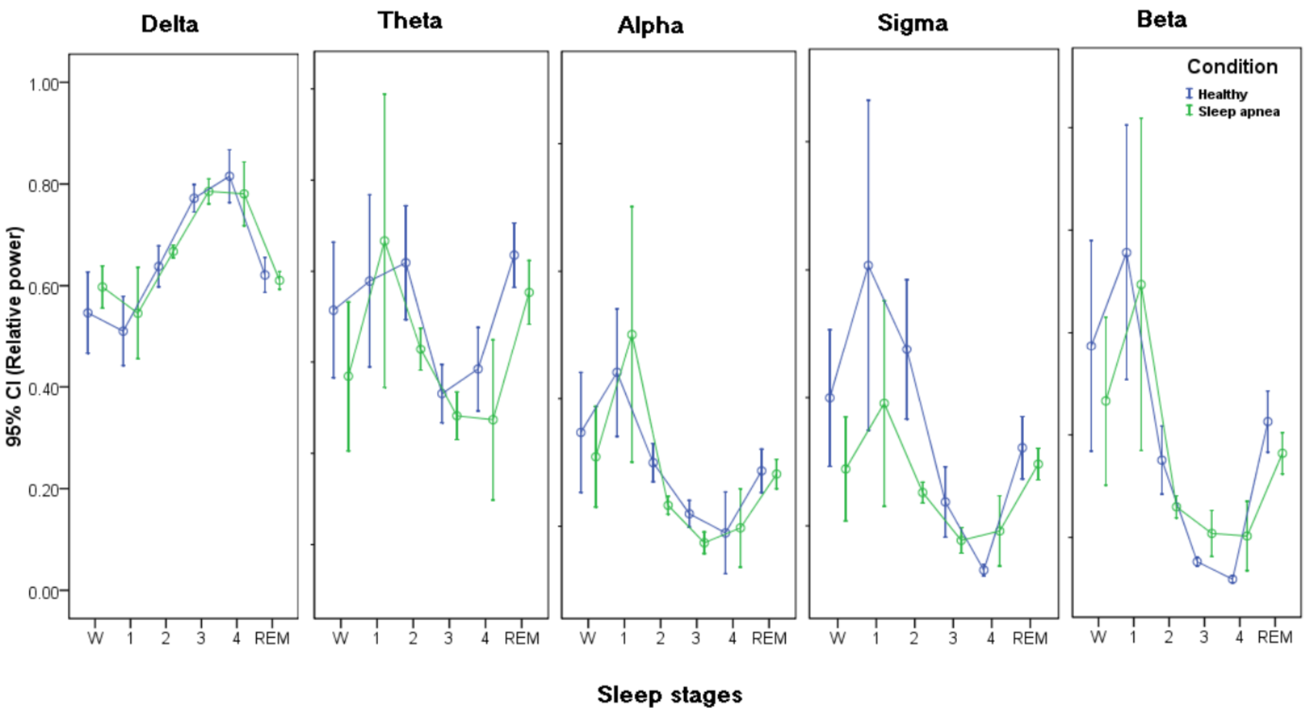

Fig 2. Comparison of mean relative power and 95 confidence intervals (CI) of five EEG frequency bands (delta, theta, alpha, sigma and beta) versus sleep stages in the healthy and sleep apnoea patients.

TABLE II. CORRELATION COEFFICIENTS BETWEEN EEG FREQUENCY BANDS AND HEART RATE VARIABILITY PARAMETERS DURING DIFFERENT SLEEP STAGES IN THE HEALTHY GROUP (H) AND SLEEP APNOEA GROUP (S).

		DELTA		THETA		ALPHA		SIGMA		BETA	
		H	S	H	S	H	S	H	S	H	S
LF/HF	W	0.10	0.12	0.08	-0.13	-0.05	-0.08	-0.11	-0.09	-0.18	-0.12
	S1	0.02	0.09	0.29	-0.19	0.02	-0.25	-0.14	-0.05	-0.30	0.23
	S2	0.09	-0.04	-0.20	-0.12	-0.32*	-0.14	-0.25	-0.31**	-0.15	-0.33**
	S3	-0.36*	0.29*	-0.06	0.12	0.05	-0.07	-0.22	-0.04	-0.18	-0.17
	S4	-0.88**	0.14	-0.17	0.01	0.21	-0.06	0.28	-0.09	0.25	-0.08
	REM	-0.29*	-0.04	-0.06	0.05	0.11	-0.15	-0.18	-0.32*	-0.16	-0.31*
LFNU	W	0.21	0.23	0.22	-0.01	-0.04	-0.24	0.01	0.03	-0.13	-0.04
	S1	-0.07	-0.09	0.48*	-0.13	0.26	-0.17	0.02	0.13	-0.16	0.26
	S2	0.03	-0.05	-0.09	-0.06	-0.20	-0.13	-0.37*	-0.33*	-0.09	-0.43*
	S3	-0.25	0.39**	-0.11	0.20	0.06	-0.18	-0.29*	-0.13	-0.29*	-0.25
	S4	-0.79*	0.22	-0.41	-0.10	0.63*	-0.18	0.20	-0.24	0.15	-0.24
	REM	-0.30*	-0.01	-0.02	0.08	0.14	-0.19	-0.10	-0.32**	-0.08	-0.32**
HFNU	W	-0.18	-0.12	0.06	0.08	0.29*	0.21	0.17	0.03	0.14	-0.03
	S1	-0.25	-0.22	-0.07	0.47*	0.21	0.25	0.28	0.15	0.41*	0.07
	S2	-0.14	0.13	0.11	0.26*	0.20	0.13	0.31*	0.29*	0.15	0.35*
	S3	0.39*	-0.27*	0.01	-0.08	-0.04	0.04	0.09	-0.01	0.19	0.09
	S4	0.74*	-0.01	0.07	-0.20	-0.18	-0.16	-0.20	-0.17	-0.15	-0.16
	REM	0.20	0.05	0.05	-0.11	-0.18	0.05	0.15	0.24*	0.16	0.21*

*Alpha level at P<0.05, ** Alpha rate correction at P<0.001.