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Phase Synchronization and Directional Coupling Between Brain and Heart During Sleep

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Abstract— **Phase synchronization is a measure of interaction between phases of two chaotic systems although their amplitudes are uncorrelated. Here, we investigate the synchronization between heart signals and EEG frequency bands (delta1, delta2, theta, alpha1, alpha2, sigma, beta and gamma) during sleep Stage 1-4 and REM in the healthy and sleep apnoea by means of Synchronization Index (*SI*) and Directionality Index (*d*). The results showed that in both groups and all sleep stages, there was a strong unidirectional coupling from brain to heart.**

Keywords- EEG, ECG, phase synchronization, directionality, sleep

I. INTRODUCTION

The human cardiovascular and neurological systems are two systems that do not act independently. Their interaction is rather complex and still remains a subject of physiological research. The EEG which records the cerebral activity of the brain is a part of central nervous system (CNS) that is connected to autonomic nervous system (ANS) that regulates cardiac activity through peripheral nervous system (PNS).

Although, many different types of linear and nonlinear synchronization techniques have been applied to study the interaction between heart and brain during normal sleep and apnoea, the understanding of directional mechanism ('who drives whom') of these two complex biological systems remains uncertain [1-6].

In [7], we have reported 'driver-response' relationship from the raw signals of EEG and ECG by using a non-linear interdependence measure. We have found that the brain is dependent more on the heart electrical activity, in other words the information that flows from the heart, actually modulates the brain electrical activity. To validate our previous study, we have to compare the directional measures by using other approach; in this case we use Phase Synchronization (PS).

EEG and ECG signals apparently may have uncorrelated amplitudes; however by transforming the original signal into its phase space, the two signals may synchronize at time *t* following the phase locking condition. This concept of Phase Synchronization (PS) has been used successfully in the study of cardiac and respiratory interaction as well as in the neurophysiological applications [8-13].

The aim for this study is to investigate how the phase of heart rate of ECG and different EEG frequency bands are interacted during different sleep stages in the healthy and sleep apnoea. By means of phase-phase coupling, we further interested to identify the coupling direction between heart and brain signals.

II. MATERIAL AND METHODS

A. Data

An eight-hour PSG with scored sleep stages were recorded with sampling frequency of 256 Hz at St. Lukes Hospital (Sydney, NSW, Australia). Eleven patients (9 male and 2 female) with an average Apnoea-Hypopnoea Index (AHI) 48.97 ± 27.52, BMI 32.92 ± 5.30 (kg/m2), age 50.64 ± 11.39 years were recruited for an overnight study at the sleep laboratory. Eight healthy patients (5 male and 3 female) AHI 2.75 ± 1.22, age 48.13 ± 10.52 years with BMI 27.01 ± 2.94 kg/m2 were also included in this study. In this experiment, EEG channel C3-A2 and Lead II of ECG were used to analyse the interaction between heart and brain. From the PSG, any EEG and ECG epochs that have muscular, noise and ocular artefacts were visually screened and discarded so that only a clean signal was selected. Further, the correspondence time segment for EEG and ECG signals were analysed using 30 s windows. Fig.1 shows a block diagram of computational process of phase synchronization methods used in this paper.

B. Preprocessing

Before computing instantaneous phase for EEG, we have filtered the EEG raw signals into eight frequency bands as delta1 (0.5-2Hz), delta2 (2-4Hz), theta (4-8Hz), alpha1 (8-10Hz), alpha2 (10-12Hz), sigma (12-14Hz), beta (14-30Hz), gamma (30-45Hz), refer Fig. 2. This filtering process was done by using linear finite impulse response filter from EEGlab Toolbox function eegfilt.m [14].

R-peaks of ECG signals were detected using Pan and Tompkins algorithms as following [15]:

1. The ECG signals were detrended to remove DC bias by subtracting the mean from the original signals.

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2. Bandpass filtering by using cascaded Finite Impulse Response (FIR) high-pass and low-pass filters to remove 50Hz powerlines interference, baseline wonder and movement noises.
3. Differentiation, squaring and integration by using moving window.
4. Applying adaptive threshold to detect R-peaks.

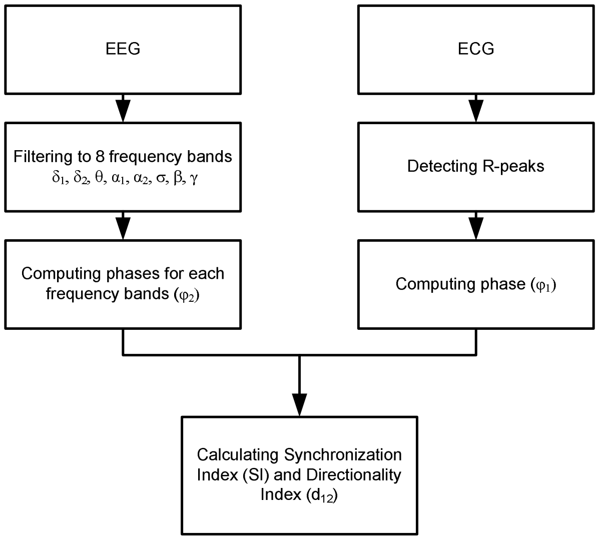

Fig. 1 Block diagram of computational phase synchronization

C. Phases

1. *Instantaneous phase ($\theta(t)$) or protophase*

The instantaneous phase of EEG were estimated via the Hilbert Transform (HT)

$$\zeta(t) = s(t) + \imath s_H(t) = A(t)e^{\imath\theta(t)} \quad (1)$$

$$\theta(t) = \arctan\left(\frac{s_H(t)}{s(t)}\right) \quad (2)$$

where $s_H(t)$ is HT of original signal $s(t)$, $A(t)$ represents an amplitude and instantaneous phase.

From the series of R-peaks event, we computed the instantaneous phase for ECG via marker events method as suggested in [8]:

$$\theta(t) = 2\pi k + 2\pi \frac{t - t_k}{t_{k+1} - t_k}, \quad t_k < t < t_{k+1} \quad (3)$$

where t_k , k = 1, 2,… is the time of R-peaks point events taking place. By using this method, it is assumed that the time intervals between two R-peaks represent one complete cardiocycle (Fig.3).

2. True phase ($\dot{\phi}(t)$)

To obtain the true phase from the protophase, we have implemented method from [16]. The details on the technique are available at [16]. By using this method, each signal is mathematically modeled by means of function

$$\Delta\phi_{1,2} = \omega_{1,2}\tau + F_{1,2}(\phi_{2,1}, \phi_{1,2}) \quad (4)$$

Here, $\Delta\phi_{1,2}$ is a phase difference between two systems and function $F_{1,2}$ is a smooth function obtained from the model.

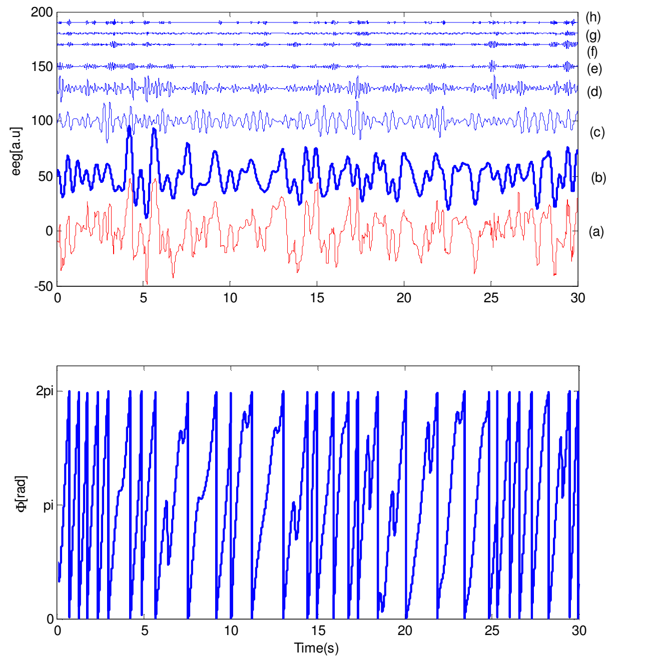

Fig. 2 A segment of 30 s of (a) original EEG signals, (b)-(h) are the filtered signals at delta1, delta2, theta, alpha1, alpha2, sigma, beta and gamma respectively. Bottom figure is a phase plot of signal (b)

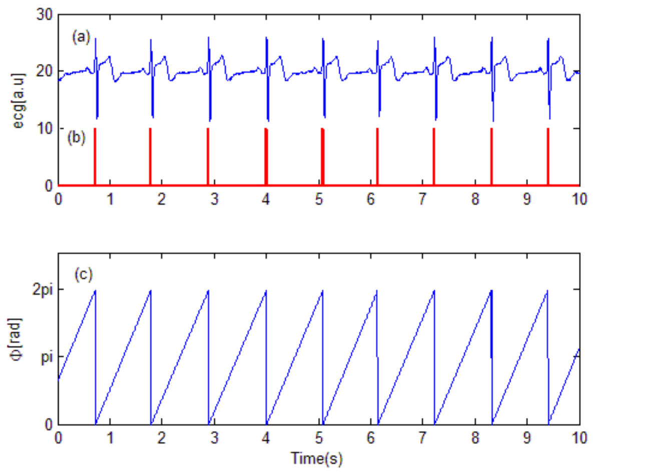

Fig. 3 A segment of 10 s of (a) ECG, (b) detected R-peaks and (c) instantaneous phase of R-peaks

D. Phase Synchronization Measures

1) *Synchronization Index (SI):*

$$\gamma_{n,m} = \left| \left\langle e^{i(n\theta_1 - m\theta_2)} \right\rangle \right| \quad (5)$$

where θ_1 and θ_2 is the phase of signals x and y average over time. n and m is set to 1 in our study. If the two signals are phase synchronized, the *SI* will approach the maximum value of 1 and the value is near to zero if the signals are not synchronized [8].

2) *Directionality Index (d):*

$$d^{(1,2)} = \frac{c_2 - c_1}{c_1 + c_2} \quad (6)$$

where

$$c_{1,2} = \frac{N^{(1,2)}}{\omega_{1,2}} \quad (7)$$

This index d varies from -1 for unidirectional coupling (2 drives 1 - brain drive heart) to 1 in opposite direction (1 drives 2 – heart drives brain). In the case of bidirectional coupling, the index value is $-1 < d < 1$. This index is also a measure of coupling strength of driven systems [9].

The computation of SI and DI were performed by Matlab toolbox, DAMOCO [16].

III. RESULTS

1. Synchronization Index (SI)

Table 1 shows the mean values for SI during different sleep stages. In most of EEG frequency bands except for delta1 and delta2, the SI between heart and EEG signals for apnea group were higher than the healthy group. Both groups showed a decrease in SI values from sleep Stage1 to Stage 4 and clearly regained it values during REM.

2. Directionality Index (d)

In both groups and for all sleep stages, the index showed the tendency towards a dominant of unidirectional interaction (from brain to heart) as the frequency of EEG increased (Fig. 4). These were reflected by a negative values obtained from $d_{1,2}$. It was also observed that in the apneic, the directional index was slightly higher than the healthy. The directional index for EEG delta1 bands and R-peak phase for both groups and in all sleep stages were significantly lowered compared to the other frequency bands.

TABLE I

MEAN VALUES OF SI BETWEEN PHASE OF R-PEAKS AND EEG FREQUENCY BANDS AT DIFFERENT SLEEP STAGES (STAGE1-4) AND REM IN THE HEALTHY AND APNEA GROUPS

		SI				
		S1	S2	S3	S4	REM
Delta1	Healthy	0.184	0.183	0.179	0.174	0.185
	Apnea	0.175	0.182	0.175	0.171	0.179
Delta2	Healthy	0.033	0.033	0.033	0.033	0.033
	Apnea	0.027	0.028	0.028	0.029	0.028
Theta	Healthy	0.017	0.017	0.016	0.015	0.018
	Apnea	0.017	0.017	0.016	0.017	0.017
Alpha1	Healthy	0.022	0.019	0.019	0.017	0.022
	Apnea	0.029	0.024	0.025	0.019	0.026
Alpha2	Healthy	0.028	0.025	0.024	0.022	0.028
	Apnea	0.037	0.030	0.031	0.024	0.033
Sigma	Healthy	0.031	0.029	0.027	0.024	0.031
	Apnea	0.046	0.038	0.041	0.032	0.041
Beta	Healthy	0.027	0.025	0.023	0.020	0.028
	Apnea	0.038	0.031	0.031	0.023	0.034
Gamma	Healthy	0.058	0.059	0.056	0.054	0.062
	Apnea	0.089	0.078	0.081	0.065	0.083

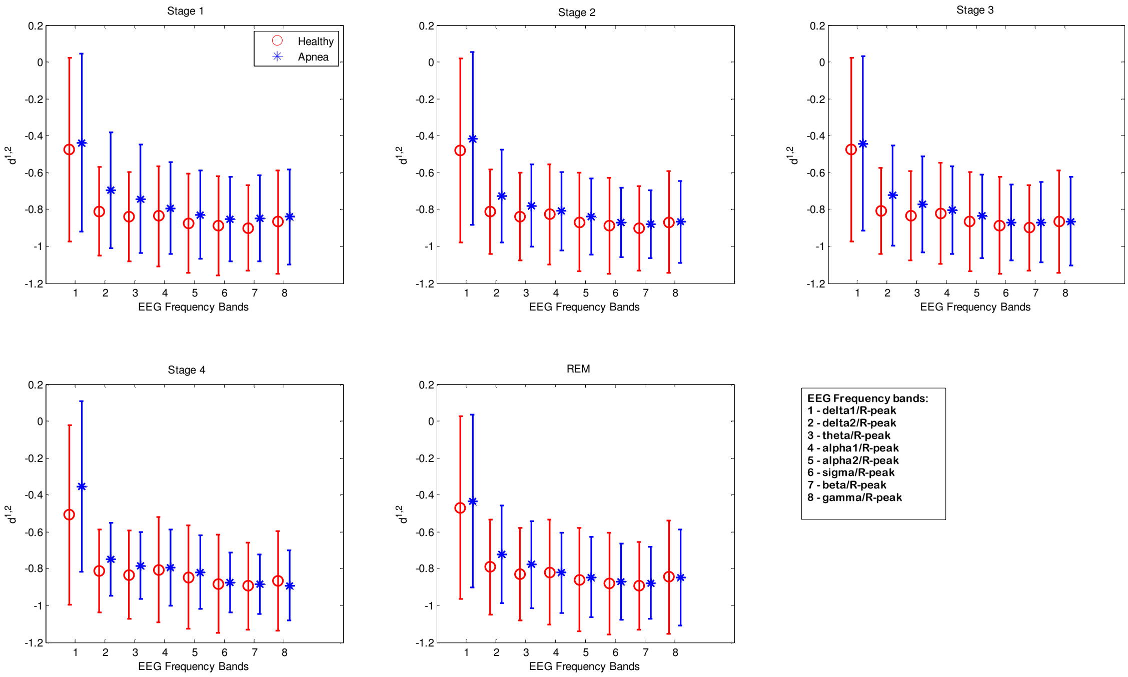

Fig. 4 Directional index, $d_{1,2}$ (mean ± standard deviation) versus R-peak phase and EEG frequency bands for sleep stages 1-4 and REM in healthy (circle) and apnea (asterisk)

IV. DISCUSSION

In this paper, we have analysed the interaction between human heart and different EEG frequency bands by using phase synchronization methods. Two parameters have been extracted namely, *SI* and $d_{1,2}$ during sleep stages 1-4 and REM. In general, high values of synchronization index were interpreted as an evidence of strong functional connectivity existed between two systems. In agreement with previous study that has used linear method of coherence, we found that the highest *SI* was also observed in delta band [17]. During sleep, brain cortex becomes more inactive from Stage 1 to Stage 4 and reactivates during REM which depends on available number of neuron for processing information. We detected this process has a similar role on the *SI* trend from light sleep to deep sleep and followed by REM whereas the indexes decreased and increased accordingly to this underlying process. A lower value of SI in apnea for delta bands suggested a reduction of deep sleep in this group compared to the healthy.

Although a directional index values between -1 and 1 indicates bidirectional coupling, the strength of the coupling in our study showed the heart depended more on the brain than vice versa. The indexes did agree in most of the EEG frequency bands except in delta bands where the strength was slightly weaker. These directional index however in contrast to our previous study, which has suggested that the information that flows from the heart actually modulates the brain electrical activity [7]. It would be a worthwhile to recall that in our earlier study, we have carried out the analysis on the raw data. In this study we have filtered the EEG signals into several narrow band signals and have used a series of R-peak in computation the phases. Therefore, the interaction between heart and brain has been unmasked in more depth which cannot be seen in the previous study. Contrary to the previous report [18], which has suggested cardiac oscillator is driving the neural activity; our study has an advantage in terms of number of subject we have analyzed in studying the phase synchronization. The limitation of this study was we do not apply any surrogate data methods to validate the results. The study of phase amplitude coupling between EEG frequency bands and heart rate variability narrow bands are currently being carried out and will be published elsewhere.

V. CONCLUSIONS

The results presented in this work have showed the existence of neurocardiologic interaction with a clear signature of brain driving the cardiac in all sleep stages and in both groups.

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