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Mutual Information Between EEG and Cardiorhythmogram Signals in Various Spectral Bands

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Abstract - **In this paper the problem of assessment the interconnection between electroencephalogram (EEG) and cardiorhythmogram signals is addressed. Power spectral density of various EEG and cardiorhythmogram signals calculated in time windows that were shifted along the signal were chosen as input parameters for mutual information (MI) calculations. All the MI values between calculated parameters were significantly different from surrogate ones that was proven by Wilcoxon rank-sum tests, suggesting the existence of substantial interconnections between heart and brain activity.**

Keywords - **Mutual Information, EEG, Cardiorhythmogram.**

I. INTRODUCTION

Recently the amount of interest was raised to study of interconnectivity between brain and heart functioning by means of analyzing electroencephalogram (EEG) and electrocardiogram (ECG) signals. The motivation is to develop systems for automated sleep staging [1] and apnea detection [2], study cardiovascular dysfunction [3], Alzheimer’s disease [4], etc.

There are number of studies that investigate connectivity between EEG and cardiorhythmogram signals by means of correlation analyses [5–7], but there are a plenty of other mathematical techniques to quantify the coupling from two signals. One of possible techniques to estimate connection is mutual information (MI), which can detect linear and non-linear statistical dependencies between time series [4].

Since power spectral analysis is a well-established method for the analysis of EEG and cardiorhythmogram signals, in this work is decided to use power spectral densities as parameters for MI calculations. Our attempt is to study possible linear as well as non-linear interconnections between signals reflecting brain and heart functioning using their power spectral densities in various spectral bands.

II. MUTUAL INFORMATION

Mutual information is defined by the formula [8]:

$$I(\mathrm{X};\mathrm{Y}) = \sum_{y\in Y}\sum_{x\in X} p(\mathrm{x},\mathrm{y})\log\left(\frac{p(x,y)}{p(x)\mathrm{p}(y)}\right)$$

where $p(x,y)$ is the joint probability distribution function of random variables X and Y, and $p(x)$ and $p(y)$ are the marginal probability distribution functions of X and Y respectively. High value of mutual information between two signals represents a large reduction of uncertainty about one random variable given the knowledge of the other and zero value indicates the independence of random variables.

III. METHODS

To analyze connectivity between EEG and cardiorhythmogram signals, power spectral densities (PSD) of α, β, δ, θ, γ EEG frequency bands and PSD of LF (low frequency, 0.05-0.15 Hz), HF (high frequency, 0.15-0.4 Hz), VLF (very low frequency 0.03-0.05) [9], LF/HF ratio of cardiorhythmorgram were employed. Total power of signals in full range of frequencies was also related to powers in each frequency bands (designated by P_{EEG} and P_{rhythm} respectively). PSD is calculated in 30 seconds artefact-free windows with 5 second shifts across the signal. Surrogate signals are obtained by random permutations of PSD values in order to destroy any linear and non-linear dependence but preserve the initial signal amplitude distribution [10].

To estimate significance of connectivity, it is proposed to calculate the ratios between calculated MI values and surrogate ones. To further prove or dethrone the difference between them the Wilcoxon rank sum test is used since calculated parameters tend to be non-normally distributed 2data, which is proven by Kolmogorov-Smirnov tests.

IV. EXPERIMENT

In the experiment simultaneously recorded EEG and ECG signals of 16 healthy children during sleep were chosen. In Fig. 1 the example of a part of the signals that

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were used for analysis can be seen. EEGs were recorded from 19 scalp loci (Fp1, Fp2, F7, F3, Fz, F4, F8, T3, C3, Cz, C4, T4, T5, P3, Pz, P4, T6, O1, O2) of the international 10-20 system with reference to ipsilateral ear. One ECG channel recorded from II standard Einthoven's lead can be seen in the bottom of the figure. This ECG was used for derivation of RR-intervals for further spectral analysis.

The artifact-free regions with minimal duration of 2 minutes were selected, which resulted in parts of signals with overall duration of 5 hours with sampling frequency 250 Hz.

After signal recordings, the power spectral parameters were calculated for EEG and cardiorhythmorgram according to the experiment setup described in previous section.

In Table 1 the mean as well as standard deviation values of ratio between MI calculated between chosen parameters and MI on 20 surrogate datasets are shown for Fp1 EEG channel. In Table 1 the cases with 5 largest mean ratios are shown in bold.

V. DISCUSSION

The results of this paper as can be seen from the Table I show that MI values between each of the calculated parameters were significantly different from surrogate ones that was proven by Wilcoxon rank-sum tests. It can be concluded that there exists a significant connection between overall PSD of cardiorhythmogram and PSD of EEG, as well as PSD in α , β , γ frequency ranges.

Since this connection between signals representing the functioning of brain and cardiovascular system is defined for the frequency characteristics of underlying oscillations, the physiologically justified basis might be revealed from this fact. For this reason further research on the diagnostically meaningful features of the oscillations in respective frequency bands of EEG and cardiorhythmogram should be analyzed simultaneously.

The novelty of the research results obtained in this paper lays in calculation of MI between PSDs in windows that are shifted along the signals for all EEG and cardiorhythmogram frequency bands that provide basic information on power distribution across the frequencies. The new approach proposed here makes possible to differentiate between real signals and the signal without dependence that were obtained with random permutation of PSD values.

Using the approach proposed in this paper, it may be possible to differentiate between the physiological states or human diseases if the values of MI are changing

TABLE I

MEAN AND STANDARD DEVIATION OF $\frac{I}{I_{surr}}$ RATIO FOR CALCULATED SIGNAL PARAMETERS AND FP1 EEG CHANNEL

	P_{EEG}	alpha	beta	theta	delta	gamma
P_{rhythm}	**2.93 ±0.56**	**3.13 ±0.60**	**3.14 ±0.6**	2.9± 0.58	2.5 ±0.48	**4.75 ±1.12**
LF	1.97 ±0.42	1.82 ±0.35	1.95 ±0.37	2.10 ±0.40	2.04 ±0.43	2.60 ±0.64
HF	2.08 ±0.43	2.16 ±0.41	2.29 ±0.42	2.02 ±0.38	1.80 ±0.35	**2.82 ±0.67**
VLF	1.70 ±0.37	1.48 ±0.266	1.51 ±0.27	1.60 ±0.29	1.82 ±0.39	1.93 ±0.55
LF/HF	2.00 ±0.42	1.46 ±0.28	1.71 ±0.35	1.63 ±0.30	2.15 ±0.46	**3.20 ±0.87**

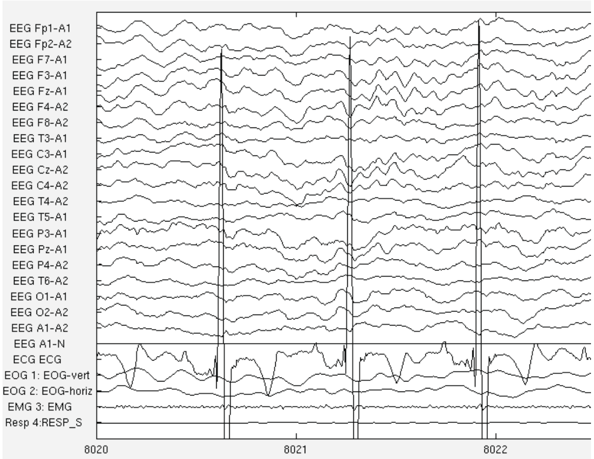

Fig.1. An example of a part of initial signal. ECG signal is overlapping the EEG signal channels due to the larger amplitude

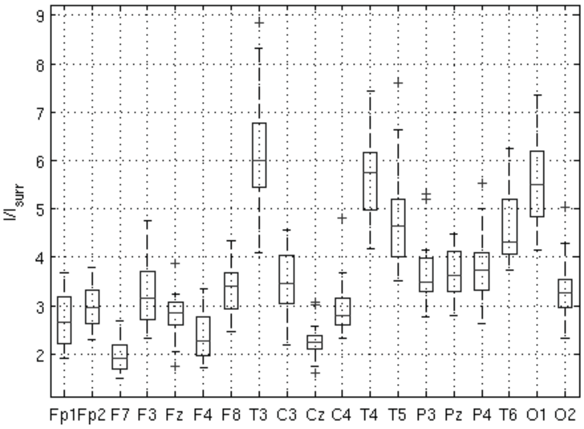

Fig.2. Box plots of $\frac{I}{I_{surr}}$ ratios calculated between P_{EEG} and P_{rhythm} for 20 surrogate signals.

accordingly to that state and this phenomena should it be further studied. The new analysis framework proposed in this paper was applied to the signals from healthy children during sleep for the first time, but the same approach and may be extrapolated on any database of EEG and cardiorhythmogram signals. This allows studying connections between any groups of parameters from any systems as well.

In Fig. 2 box plot of the ratios between MI calculated for real PSD sequences and surrogated ones for every EEG channel is presented. Central mark is the median, the edges of the box are the 25th and 75th percentiles, the whiskers represent the most extreme points and outliers are plotted as plus mark. It can be seen that for some EEG channels, namely T3, T4 (midtemporal electrodes), T5 (posterior temporal) and O1 (occipital) ratios are definitely higher than for other EEG channels with median values reaching ratio of 6. This result might suggest the way of finding the areas of the cortex which are responsible for the connection or control of heart activity. To do this, more clinical studies should be conducted.

Obtained results are very promising in a sense that they allow to proceed with other signals and parameters of connectivity between brain and heart. It is also beneficial to investigate the change of MI with increasing windows' duration, step between them and with introducing time delays to the analyzed signals.

IV. CONCLUSION

In the presented work the connectivity between the EEG and cardiorhythmogram signals was assessed using mutual information.

MI between PSDs in windows that are shifted along the signals for all EEG and cardiorhythmogram frequency bands that provide basic information on power distribution across the frequencies was calculated. It was statistically proven in comparison with surrogate data that there is the coupling between EEG and cardiorhythmogram signals. It was determined that the channels of EEG with strongest connection to the cardiorhythmogram for the case of overall PSDs calculated in windows are gamma and beta channels. The strongest connectivity between frequency bands are between EEG beta activity and high frequency band of cardiorhythmogram.

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