Spectral, Complexity and Interdependence Measures of Sleep EEG after Ischemic Stroke

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Abstract. *The study focused on separation of sleep electroencephalogram (EEG) of patients after ischemic stroke and sleep EEG of healthy subjects. A prognostic value of the characteristics as regards patients' recovery was also studied. Many spectral measures and measures of complexity and interdependence were evaluated for EEG of 50 patients and 52 healthy subjects. The patients had higher sleep efficiency, and they spent more time in slow-wave sleep (SWS) but less time in rapid eye movement sleep in comparison to controls. During waking, high delta power relative to the reduced power of alpha and faster waves was found after stroke. During SWS, on the contrary, fewer delta waves and more of faster waves was observed in EEG of patients as compared to controls. The complexity of EEG of patients was lower during wake and higher in SWS in comparison to healthy subjects. Interdependence between the hemispheres was found to be lower for the sleep EEG of patients. It was also found that, the lower relative power in 4-8 Hz and higher relative power in 30-40 Hz of EEG 5-7 days after stroke, the worse prognosis regarding withdrawal of symptoms within the next 90 days.*

Keywords: Sleep EEG, Stroke, Complexity Measures, Spectral Measures, Coherence

1. Introduction

Dyken et al. [1] found an increased incidence of obstructive sleep apnoea in a group of patients with a recent stroke compared with sex- and age-matched control subjects. Moreover, all patients who died within the next 4 years had obstructive sleep apnoea. According to Gur et al. [2] EEG slowing after stroke can be associated with higher risk of developing dementia. In [3] the authors have found that the lower the brain symmetry index (BSI) the worse the condition of the patient rated by the National Institute of Health Stroke Scale (NIHSS). In [4] high delta power relative to reduced alpha power in the ischemic hemisphere and increase of BSI shortly after stroke have been found to be the most reliable indicators of unfavorable prognosis. Good outcomes have been predicted by an absence of these phenomena [3], [5].

Zappasodi et al. [6] have found that decrease of the fractal dimension (FD) in stroke patients has been paired to a worse acute clinical status. The reduction has been larger in the affected hemisphere with respect to the intact one. Moreover, the unbalance between the complexities of the hemispheres has been found to be related to a worse recovery at 6 months.

In this paper, first, the data and the methods are described and the hypnograms are created by automatic scoring. Then 65 characteristics estimated across the individual sleep stages are investigated. Finally, the features that are promising in terms of distinction between the two groups of subjects and in terms of prognostic value are selected.

2. Subject and Methods

Data

In total, 102 all-night EEG recordings were analyzed, 50 of them belonged to patients after stroke and 52 were measured in a healthy control sample. Signals from electrodes C3-M2 and

C4-M1 were used, where M1, M2 are the left and the right mastoids, following the 10-20 international electrode placement system. The sampling frequency was 100 Hz. The recordings of patients (24 men and 26 women) had been collected in the hospital within 5-7 days after the occurrence of ischemic stroke. The lesions were confined to the right hemisphere. The average age of subjects was 70 years, the youngest patient was a 39-year-old woman, and the oldest one was an 88-year-old woman. The recordings took 7.53 hours in average (0.87 stand. dev.). The NIHSS ranged from 0 (no stroke symptoms) to 11 (while the maximum possible score value is 42), reflecting the fact that our data corresponded to strokes without severe motoric or speech impairment. The control sample was taken from the SIESTA database of polysomnographic recordings healthy adults [7]. To avoid age-related bias, only subjects over 60 have been included in the analysis. Subjects slept typically from 11 pm, the average recording time was 7.97 hours (0.46 stand. dev.).

Automatic Sleep Classification

The scoring of the sleep, called hypnogram, is based on the rules of Rechtschaffen and Kales [8]. The rules are built on the fact that the spectral characteristics of recordings change markedly between different levels of sleep. All 30 sec pieces of an all-night recording are classified into one of the next stages: wakefulness (W), the lightest sleep Stage 1 (S1), sleep Stage 2 (S2), the deepest stages S3 and S4 referred to as SWS here and the rapid eye movement sleep (REM). To obtain the hypnograms for our data, we have designed an automatic classifier based on spectral and nonlinear characteristics of EEG that have proven to be effective for automatic scoring of sleep stages in the previous studies [9], [10].

Measures used for the analysis

We computed 65 characteristics for the same 30 sec long intervals, which were used for sleep scoring. A detailed description of the measures can be found in [9]. First of all, traditional sleep characteristics including the total sleep time, the sleep efficiency, and the time spent in individual sleep stages were derived directly from the hypnograms. Secondly, average amplitude, the percentile of the values, zero-crossing rate, variance, skewness, kurtosis, relative spectral powers, relative power ratios, spectral mean, spectral edge, spectral variance, spectral skewness, and spectral kurtosis were computed. Spectral power was computed in the next frequency bands: delta 1 (0.5 - 2 Hz), delta 2 (2 - 4 Hz), theta 1 (4 - 6 Hz), theta 2 (6 - 8 Hz), alpha 1 (8 - 10 Hz), alpha 2 (10 - 12 Hz), sigma 1 (12 - 14 Hz), sigma 2 (14 - 16 Hz), beta (16 - 30 Hz), gamma (30 - 40 Hz). The total power was computed from the frequency band 0.5 - 40 Hz. Relative spectral powers were stated as ratios of absolute powers in specific bands to the total spectral power. In addition, ratios between the relative spectral powers were also computed: delta/theta, delta/alpha, and so on. The third class of characteristics included Shannon and spectral entropy, fractal exponent and dimension, Hurst exponent, and prediction error. Coherences in 10 frequency bands, capturing linear dependence and mutual information as a measure of a general mutual dependence of two variables was also computed.

The statistical significance of differences among the histograms of the characteristics was tested using the two-sample Kolmogorov-Smirnov test.

3. Results and Discussion

Outcomes of simple hypnogram based characteristics.

In contrast to our results (Table 1), in work of Jiang et al. [11] patients with simple stroke or vascular cognitive impairment have been declared to experience decreased sleep efficiency, and reduced total sleep time and SWS in comparison to controls. In fact, we only agreed with

Jiang et al. in the finding that time spent in REM was shorter for patients than for the healthy sleepers.

Table 1. The results derived from the hypnograms. Total sleep time (TST), sleep efficiency (SE), and relative time in % spent in the individual sleep stages. Mean values (standard deviations in parentheses).

	Healthy	Stroke
TST [h]	6.12 (0.90)	6.41 (1.23)
SE [%]	76.85 (11.39)	85.08 (16.33)
W	23.15 (11.39)	14.92 (16.33)
S1	18.31 (8.13)	26.05 (16.08)
S2	34.91 (7.73)	26.24 (12.71)
SWS	12.44 (8.38)	26.45 (16.62)
REM	11.19 (6.10)	6.35 (6.10)

Outcomes of spectral, complexity, and interdependence measures

Fig. 1 shows that, even though patients spent more time in SWS, they did not sleep as deeply as healthy sleepers. By this, we mean that the stroke EEG contained more power in higher frequency bands relative to low frequencies. On the other hand, while awake, the EEG of the patients showed more power in low frequencies (and a lower level of complexity, $p < 0.05$) than the EEG of the healthy controls. Partially similar results - increased delta relative to reduced alpha power after stroke, has been presented in [4]. This is consistent with the rising hypothesis about complexity decrease of the wake EEG after various types of brain damage. If we put the most pronounced differences together, ratio delta 1 / beta was significantly higher ($p=0.04$) in stroke EEG during wake and lower ($p=0.01$) during SWS than in control EEG. Moreover, the proportions increased with age of the subjects and the severity of the stroke.

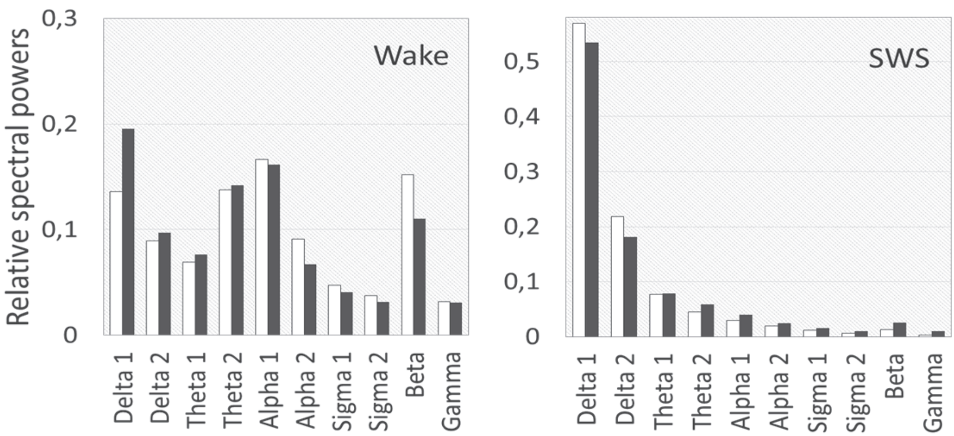

Fig. 1. Relative spectral powers in 10 frequency bands during wake and SWS. Averages computed from EEG of 50 patients after stroke (black) and 52 healthy controls (white).

The co-operation of the hemispheres, evaluated by coherence and mutual information, was found to be lower ($p=0.02$) in stroke patients than in healthy volunteers (Fig. 2). This was true for all sleep stages and - in respect of coherences - most pronounced in delta and theta bands.

The cooperation between the left and right hemispheres of patients was even decreasing with the severity of the stroke. The decline was most apparent for sigma-coherence (probably another manifestation of the loss in sigma power after stroke) and coherences during the REM sleep (likely related to disturbance of REM sleep due to stroke).

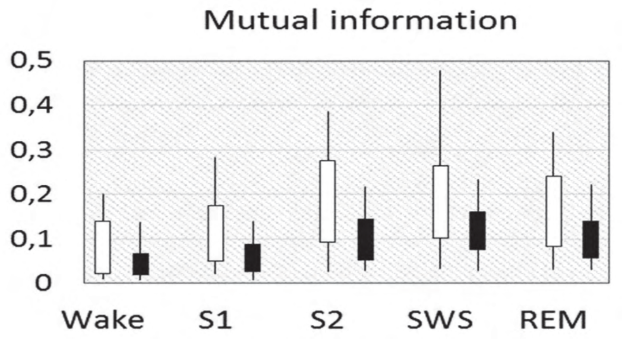

Fig. 2. Mutual information between C3-M2 and C4-M1 channels computed for each sleep stage. Averages from EEG of 50 patients after stroke (black) and 52 healthy controls white)

Healthy-stroke classification

As some features have proved to be very useful in distinguishing between sleep EEG after stroke and healthy sleep EEG, a classifier was built analogously as in the case of the classification of sleep stages [10]. The system was based on a support vector machine, which classified data by finding the best hyperplane that separated stroke EEG segments from the segments of the control group. The resulting classifier reliably distinguished healthy brain signal from EEG affected by stroke.

Predictive value of the outcomes

To touch the topic of the predictive value of EEG characteristics, we compared the NIHSS score of patients 5-7 days after stroke with their condition (expressed by NIHSS again) 90 days later. We selected 32 patients with NIHSS values starting between 3 and 11. Of these, five were without symptoms (NIHSS = 0) after 90 days, another five have not improved, and the remaining 22 experienced only a slight improvement. Literature highlights two statistically significant indicators of unfavorable prognosis, namely the high delta power relative to reduced alpha power in the ischemic hemisphere and increase of inter-hemispheric asymmetry shortly after stroke [4]. Our results did not confirm this. Although we found higher delta/alpha power ratio and inter-hemispheric asymmetry in the EEG of stroke patients in comparison to controls, this did not correlated with the NIHSS scoring 3 months after the stroke. What we observed in our sample of patients was that, unfavourable prognosis correlated with lower relative spectral power in theta band, higher power in gamma band and higher EEG complexity. However, our selection of subjects for this particular task (5 with the best and 5 with the worst prognosis) was not large enough to declare our observations generally applicable. Besides the methods used in this study, causal relationships between the affected and the unaffected hemisphere should also be thoroughly evaluated. This we left for further research.

Finally, we have to note that, our observations did not confirm several previously published results. This inconsistency shows that the topic needs to be addressed more thoroughly.

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