

Sleep homeostasis and slow oscillations in the human sleep EEG

P. Achermann and A. Bersagliere

Abstract—Sleep homeostasis is a basic principle of sleep regulation. Slow-wave activity (spectral power in the 0.7-4.5 Hz range of the EEG) is a well-established corresponding indicator. Prominent features of the non-rapid-eye-movement sleep EEG are slow oscillations resulting from slow membrane potential fluctuations of cortical neurons. We investigated the behaviour of slow oscillations in humans under increased sleep pressure to assess their contribution to sleep homeostasis. We analyzed baseline and recovery sleep after 40 h of prolonged wakefulness. Negative half-waves, mainly reflecting down states, were defined as negative deflections between consecutive zero crossings in the 0.5-2 Hz range of the band-pass filtered EEG. Wave parameters (amplitude, number of half-waves per min and slope) were derived for two thresholds: a low threshold allowing the detection of approximately all negative half-waves and a higher one corresponding to the scoring rules of slow wave sleep. The number of detected high amplitude waves and amplitude and slope of all waves closely resembled slow-wave activity, indicating that slow oscillations contribute to sleep homeostasis.

Index Terms—EEG, sleep homeostasis, sleep regulation, slow oscillation, slow-wave activity, slow-wave slope

I. INTRODUCTION

Sleep homeostasis denotes a basic principle of sleep regulation. A sleep deficit elicits a compensatory increase in the intensity and duration of sleep, while excessive sleep reduces sleep propensity. Slow waves represent the most prominent feature in the electroencephalogram (EEG) during non-rapid-eye-movement (NREM) sleep and reflect sleep intensity. Slow-wave activity (SWA; spectral power in the 0.7-4.5 Hz range of the EEG) is a well-established marker of sleep intensity and serves as an indicator of sleep homeostasis in NREM sleep. The level of SWA at sleep onset is determined by the duration of prior sleep and waking. For a recent review see [1].

Slow oscillations (SO; < 1 Hz) in the NREM sleep EEG result from slow membrane potential fluctuations of cortical neurons, which alternate between depolarized up-states and hyperpolarized down-states. Furthermore, SO are thought to be involved in the temporal organization of other sleep rhythms such as sleep spindles and delta waves [2].

It is possible that SWA and SO can be dissociated. Previous studies have separated the two based on findings that power in the low delta (< 1 Hz) range only partially showed homeostatic behaviour. In particular, power < 2 Hz did not decline from the first to the second NREM sleep episode [3, 4]

and was not increased after sleep deprivation [5].

We combined power spectral analysis (decomposition of the signal into its constituting frequency components) with period-amplitude analysis (complementary information such as incidence and amplitude of waves) to investigate the contribution of SO to sleep homeostasis. We analyzed baseline and recovery sleep after prolonged wakefulness.

II. METHODS

EEG recordings of 8 healthy young males (23 ± 0.46 years; mean \pm SEM) during baseline and recovery sleep after 40 h of sustained wakefulness were analyzed. For details see [6]. Derivation C3A2 was band-pass filtered in the range of 0.5 to 2 Hz. Half-waves were determined as negative or positive deflections between two consecutive zero crossings in the band-pass filtered signal. The analysis was restricted to negative half-waves predominantly reflecting down states [7]. Two amplitude thresholds of $-5 \mu\text{V}$ and $-37.5 \mu\text{V}$ were applied. The low threshold allows the detection of approximately all negative half-waves; the higher one corresponds to the scoring rules of slow waves ($75 \mu\text{V}$ peak-to-peak, $-37.5 \mu\text{V}$ for negative half-waves [8]). The number of negative half-waves per min, their amplitude and slope were calculated. The slope denotes the maximal slope, i.e. the maximum absolute value of the first derivative of the signal in the descending phase (initial slope) [6, 9]. Wave parameters were averaged for 20-s epochs and matched with the corresponding sleep stages.

EEG power spectra were calculated for consecutive 20-s epochs (FFT routine, Hanning window, averages of two 10-s epochs; frequency resolution 0.1 Hz) and matched with the corresponding sleep stages. SWA was calculated as power in the frequency range of 0.7 to 4.5 Hz.

Statistical analysis was restricted to the first NREM sleep episode. To assess the effect of increased sleep pressure we compared SWA and the wave parameters of baseline and recovery sleep with paired t-tests. SWA was log-transformed prior to testing. The relationship between SWA and wave parameters was investigated by calculating Pearson correlation coefficients within subjects for both conditions. Correlations were then averaged and compared between the two conditions. Correlation coefficients were Fisher's z-transformed prior to statistical analysis.

III. RESULTS

Data of an exemplary participant during baseline sleep are illustrated in Figures 1 and 2. SWA was modulated by the NREM-REM sleep cycle and showed the typical decline in the

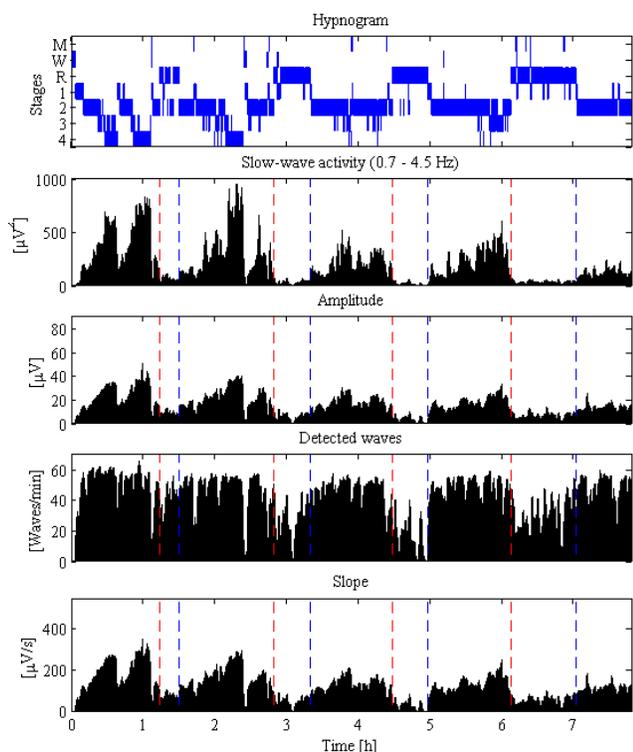


Fig. 1. Hypnogram (M: movement time; W: wake; R: REM sleep; 1-4: NREM sleep stages 1-4), slow-wave activity (SWA; spectral power in the range of 0.7-4.5 Hz) and amplitude of detected waves and slope of negative half waves detected with a threshold of $5 \mu\text{V}$ of a single individual during baseline sleep. Dashed lines delimit the beginning and end of REM sleep episodes.

course of sleep.

The wave parameters (amplitude, number of half-waves per min, slope) are depicted for two different thresholds, $5 \mu\text{V}$ (Fig. 1) and $37.5 \mu\text{V}$ (Fig. 2). The amplitude and slope of negative half-waves with amplitudes $> 5 \mu\text{V}$ (including all waves; Fig. 1) and the number of waves per min with amplitudes $> 37.5 \mu\text{V}$ (Fig. 2) closely resembled the profile of SWA. In contrast, number of waves per min with amplitudes $> 5 \mu\text{V}$ (Fig. 1) and the amplitude and slope of large waves ($> 37.5 \mu\text{V}$; Fig. 2) were more uniformly distributed across the night. In general, slope and amplitude revealed a very similar time course. A similar picture as illustrated in Figures 1 and 2 was observed in all participants during baseline and recovery nights.

Further analysis was restricted to the first NREM sleep episode where sleep pressure was highest in both conditions and the effect of sleep deprivation had not yet dissipated. The duration of the first NREM sleep episode was similar in baseline (58.2 ± 3.7 min; mean \pm SEM) and recovery sleep (58.6 ± 5.6 min; n.s., paired t-test). However, the amount of slow wave sleep (stages 3 and 4) differed between baseline (33.6 ± 7.5) and recovery sleep (47.0 ± 15.2 min; $p < 0.05$).

Sleep deprivation resulted in a significant increase of SWA, the number of waves per min and slopes for both thresholds (Tab. I). The amplitude of the negative half-waves was increased for the low threshold only. High magnitude waves

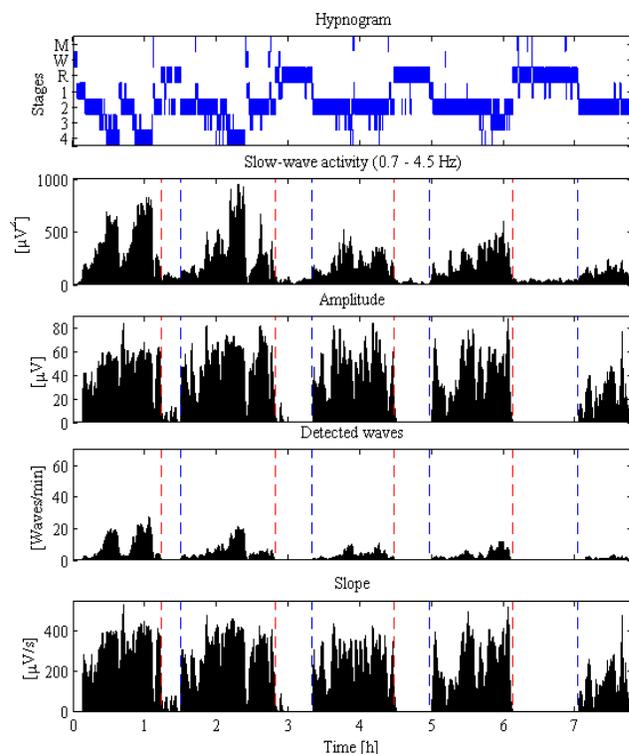


Fig. 2. Hypnogram, slow-wave activity and wave parameters detected with a threshold of $37.5 \mu\text{V}$ of the same individual illustrated in Fig. 1.

were of similar amplitude in both conditions.

The wave parameters that closely matched the profile of SWA (Fig. 1 and 2) also showed the highest correlations with SWA in the first NREM sleep episode (Tab. I). SWA correlated best with number of detected waves with the high threshold and for waves detected with the lower threshold, both in baseline and recovery sleep. The correlations between SWA and the amplitude and slope of the high amplitude waves were increased after sleep deprivation.

IV. CONCLUSION

We investigated the effect of sleep deprivation, i.e. increased sleep pressure on SO in the human sleep EEG. SO commonly encompass waves < 1 Hz [10, 11]. However, there is no physiological evidence to draw a sharp border at 1.0 Hz. In accordance with recent studies [7, 9, 12-15] we used a broader range, i.e. 0.5-2 Hz to investigate the behavior of SO.

We previously demonstrated that increased sleep pressure resulted in a redistribution of half-waves between 0.5 and 2 Hz: the number of half-waves/min was reduced below 0.9 Hz while they were increased above 1.2 Hz. EEG power was increased above 1 Hz only [6]. The current analysis focused on the entire 0.5-2 Hz range and we did not apply a finer frequency resolution.

SWA is an established marker of sleep homeostasis and was used as a benchmark to compare with wave parameters that are thought to reflect properties of SO. Our analysis revealed that the applied detection threshold for identifying SO is crucial when comparing wave parameters with SWA.

Amplitude and slope correlated best with SWA when all waves ($> 5 \mu\text{V}$) were included whereas the number of waves correlated best for high amplitude waves ($> 37.5 \mu\text{V}$) only. Riedner et al. [9] postulated that the slope of half-waves might be a better measure to assess sleep homeostasis. However, the slope is strongly dependent on both, amplitude and period (frequency of the half-wave) [6]. The high correlation between SWA and amplitude is no surprise as SWA is proportional to the square of amplitude. Thus, at least for human scalp EEG measurements there is no evidence that the slope of waves would reflect sleep homeostasis better than SWA.

We applied a zero-crossing detection algorithm to identify waves in the 0.5-2 Hz range similar to former studies [6, 9, 13, 16-18]. Our previous sensitivity analysis revealed that wave parameters are dependent on the applied cut-off frequencies of the band-pass filter [6]. However, the main results and conclusions did not depend on the cut-off frequencies. As the filter settings have an impact on absolute values of the derived measures, comparing absolute values across studies should be avoided. Oscillatory events in the sleep EEG may be detected by other approaches such as fitting autoregressive models to short EEG segments [19] which is independent of band-pass filtering of the EEG.

In summary, SO contribute to sleep homeostasis because parameters of half-waves in the range of 0.5-2 Hz were highly correlated with SWA a well-established marker of sleep intensity and indicator of sleep homeostasis.

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TABLE I
SLOW-WAVE ACTIVITY (SWA) AND WAVE PARAMETERS FOR THE TWO DETECTION THRESHOLDS (MEAN VALUES; SEM IN BRACKETS) AND CORRELATIONS BETWEEN SWA AND WAVE PARAMETERS (MEAN VALUES; RANGE IN BRACKETS). BOLD NUMBERS INDICATE SIGNIFICANT DIFFERENCES ($P<0.05$; PAIRED T-TEST) BETWEEN RECOVERY AND BASELINE SLEEP.

	Baseline		Recovery	
	threshold 5 μV	threshold 37.5 μV	threshold 5 μV	threshold 37.5 μV
SWA [μV^2]	749.3 (209.4)		1075.0 (341.2)	
Number of waves/min	54.7 (2.5)	20.1 (5.3)	57.6 (2.1)	28.9 (7.2)
Amplitude [μV]	36.7 (5.8)	62.63 (3.3)	43.9 (7.7)	62.93 (4.6)
Max initial slope [$\mu\text{V/s}$]	279.4 (40.2)	422.2 (30.5)	347.7 (56.7)	459.87 (38.65)
Correlation SWA - number of waves	-0.042 (-0.204 0.108)	0.709 (0.607 0.785)	-0.074 (-0.286 0.163)	0.615 (0.253 0.764)
Correlation SWA - amplitude	0.805 (0.755 0.855)	0.309 (0.179 0.457)	0.813 (0.766 0.905)	0.511 (0.178-0.780)
Correlation SWA - slope	0.805 (0.744 0.841)	0.422 (0.288 0.535)	0.808 (0.761 0.894)	0.584 (0.263 0.814)

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