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Sleep Depth Oscillations: An Aspect to Consider in Automatic Sleep Analysis

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The automatic sleep analysis aims at providing an accurate description of sleep process. We found that there exist so far poorly known sleep depth oscillations constantly. Quantitative analysis of these oscillations was done in this work via a mean frequency measure and FFT. Overall charasteristics of these oscillations were studied, focusing on the waves with period times of 50–150 s. These sleep depth oscillations have a relatively large amplitude and they should be considered in future sleep analysis systems. The results of this study give directions to automated sleep analysis regarding optimal estimation of sleep depth.

KEY WORDS: sleep EEG; sleep depth; automatic analysis; FFT; median filtering.

INTRODUCTION

Normal sleep is fundamental for good health. Sleep disorders cause a reduction in sleep quality, which in turn causes a lowered cognitive performance and a weakened immunological resistance. Sleep disorders are studied and treated in sleep medicine. The subject sleeps over in a sleep lab and a number of physiological signals are measured of her/him. A sleep staging[(1)] based on waveforms in electroencephalographic (EEG), eye movement (EM), and electromyographic (EMG) signals taking 3–4 h is then done visually by a medical doctor. The resulting sleep staging curve, hereafter called RKS sleep staging, has a time resolution of 30 s and following six discrete stages of sleep depth: W (wake), REM (Rapid Eye Movement), S1 (light sleep), S2, S3, S4 (deep sleep). Thus, there is quite a quantization error involved both in horizontal and vertical directions. Fairly small or short variations in the sleep process will be masked in RKS sleep staging.

Computer-based methods for sleep analysis have been and are being developed to obtain a more accurate description of sleep process.[(2–4)] It is the author's

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opinion that the most promising methods for sleep depth quantification are those using spectral complexity.[5–9]. These measures are not dependent on absolute EEG amplitudes, which is very positive as the EEG amplitudes have large inter- and intra-subject variations. Further, spectral complexity measures are based on local spectral information and thus can be used to analyze both slow and fast variations in sleep depth, even faster than 5 s, which is quite impossible in visual RKS analysis.

According to the two-process model of sleep regulation, the structure of sleep is determined by the interaction of a homeostatic and a circadian processes. There are cyclisities of multitude of time-scales in sleep depth. The most prominent cyclisity is that comprising of NREM-REM episodes of about 90 min in duration, originally described in the Ref. (10). The period time of this oscillation is thus in the order of 5400 s. Ultradian rhythms of 80–120 min have been studied extensively.[11–13] The so called cyclic alternating pattern (CAP) has also been reported.[14] It consists of fluctuations of 20–90 s, however, these variations are often present only briefly. In many publications related to computer-based analysis of sleep recordings, plots of, for example, delta band power during the night have been presented, which can be seen fluctuating.[2,15,16]

This work was initiated when we observed that there are continous oscillations in sleep depth, for instance, with a period time of about 100 s. To our knowledge, these oscillations have not been quantified before. In this work, the overall range of sleep depth oscillations was studied and those with a period time of 50–150 s were quantified and related to different sleep stages. The results of this work contribute to how a sleep depth measure should be filtered to provide optimal sleep depth information.

MATERIALS AND METHODS

Fifteen healthy subjects ($N = 15$) were studied. The group consisted of eight females and seven males, with age ranges of 24–63 and 31–52 years. All subjects were unmedicated with no sleep complaints or history of excessive daytime sleepiness. All subjects gave a written consent to participate in the study.

Two consecutive nights were recorded. The polygraphs were part of a larger study.[17] The subjects retired to bed between 10 and 12 P.M. and they were allowed to sleep maximally 8 h. Seven EEG channels Fp1-A2, C3-A2, O1-A2, Fp2-A1, C4-A1, O2-A1, A2-A1, two EOG channels, and submental muscle tonus were recorded. In addition tibialis anterior muscle tonus, body position, electrocardiogram, nasal airflow, thoracoabdominal respiratory movements, and blood oxygen saturation were recorded. Recordings were digitized with 200 Hz sampling rate. The recordings of the second night, with Sleep Efficiency Index ranging from 80 to 97% were used for the analysis.

Mean frequency was used as a spectral complexity measure in this work, as it gives a very intuitive measure of sleep depth. Anyone familiar with sleep EEG can relate to a measure that during slow wave sleep (SWS) gives readings like 2–3 Hz and during theta dominant S1 sleep around 6–7 Hz. The mean frequency of band 0.5–12.5 Hz was formed based on the spectral components on EEG bands of

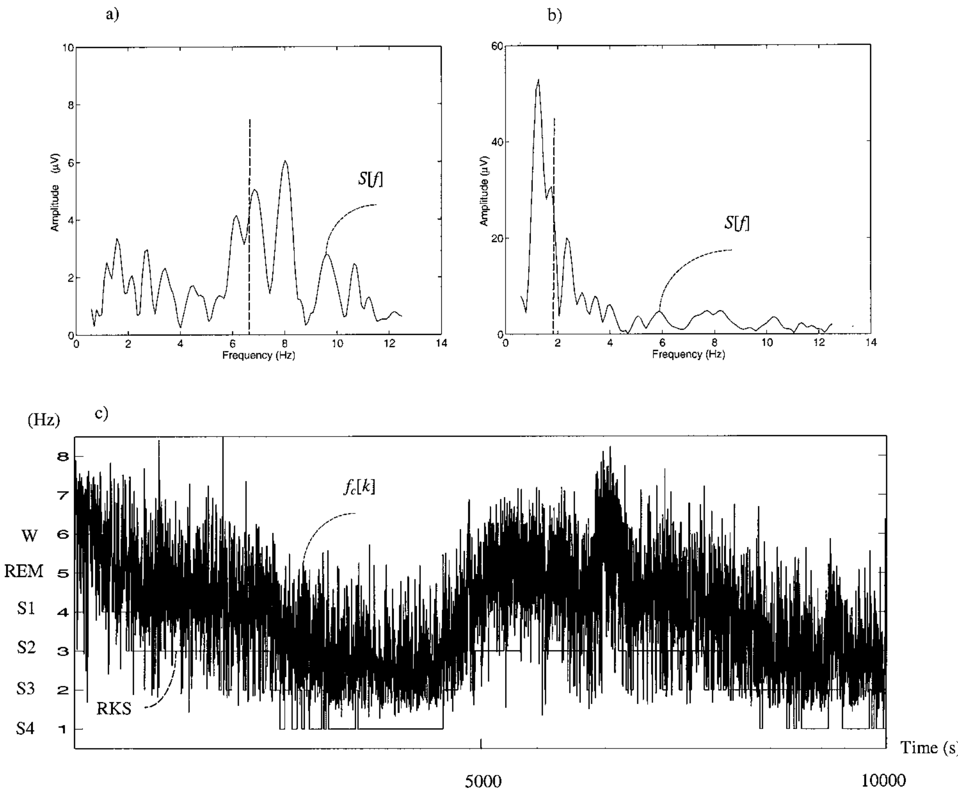

Fig. 1. Examples of mean frequency $f_c[k]$. In one case in light S1 sleep (a) $f_c[k]$ becomes 6.7 Hz (indicated with a dashed line) and in deep SWS sleep (b) $f_c[k]$ becomes 1.9 Hz. It is obviuos that if deepest sleep stage S4 is scored, there is plenty of large amplitude delta activity (0.5–3.5 Hz) and the mean frequency will inevitably become small. (c) Example of $f_c[k]$ at k ranging from 1 to 10000 s in one recording, also RKS sleep staging is seen in the background (Fig 3(a) shows an additional view to this). Deepening sleep is seen from during the first half of the segment until S4 is reached. The fast movements of $f_c[k]$ can be seen as noise in the signal.

delta (0.5–3.5 Hz), theta (4–7.5 Hz), and alpha (8–12.5 Hz) all together by finding the center of gravity of the spectrum $S[f]$ (Fig. 1(a) and (b). The unit of $f_c[k]$ is herzt (Hz).

The mean frequency $f_c[k]$ was determined using the C4-A1 EEG channel (and in time domain analysis also the other EEG channels) at 1-s time resolution. A sliding 5 s long Saramäki window[18] and zero padding to 2048 samples were used in extracting the amplitude spectrum. At the kth second, the amplitude spectrum $S[f]$ was cumulated as follows:

$$c[f] = \sum_{f=0.5}^{f} S[f] / \sum_{f=0.5}^{12.5} S[f]. \tag{1}$$

The $f_c[k]$ was obtained as $c[f_c] = 0.5$.

Quantification of Sleep Depth Oscillations

First, the mean frequency signal $f_c[k]$, providing an estimate of sleep depth, was determined in each recording (Fig. 1(c). Then, the spectral components of sleep depth oscillations contained in the signal $f_c[k]$ were studied. Amplitude spectra were extracted using a Saramäki window function of length 1000 s moving with steps of 100 s and zero padding to 2048 samples. Three frequency bands were used containing oscillations of different time scales, centered at $T = 150$, 100, and 50 s, each having a width of 40 s. These bands are denoted as $B_1 = 0.0059$–0.0077 Hz, $B_2 = 0.083$–0.0125 Hz, $B_3 = 0.0143$–0.033 Hz. The mean amplitudes in each band were collected during all the recordings. Then, the values were allocated to sleep stages so that the stages S4 and S3 were combined to "SWS" totaling 52,800 s, S1 and S2 were combined to "S2" (because there was very little S1 sleep) totaling 235,700 s, and REM consisted of a total of 90,700 s. Obviuosly, the allocation is not quite precise, but still it gives a reasonable picture.

An Attempt to Study Noise in the Signal $f_c[k]$

The mean frequency measure $f_c[k]$ clearly contains noise (Fig. 1.c), which can be written as

$$f_c[k] = s[k] + n[k], \tag{2}$$

where $s[k]$ is the sleep depth and $n[k]$ the noise process.

The question arises, how fast frequencies does the sleep process contain. An attempt was made to answer this question. As $s[k]$ and $n[k]$ both are unknown, indirect ways were needed to assess the situation. First, an average spectrum was formed during all sleep time based on the C4-A1 EEG channel (Fig. 4(a). Secondly, a fully time-domain analysis was performed with an experimentally derived (somewhat complicated) procedure as follows. Correlation between signals $f_c[k]$ of symmetric EEG channels (frontal channels Fp1-A2 and Fp2-A1, central channels C3-A2 and C4-A1, occipital channels O1-A2 and O2-A1, one hemisphere Fp1-A2 and O1-A2, the other hemisphere Fp2-A1 and O2-A1) were studied. The correlations were studied in this case in frequency bands such that oscillations of different time scales were preserved as $T = 100$–75, 75–50, 50–25 and 25–1 s (corresponding to 0.01–0.013, 0.013–0.02, 0.02–0.04 and 0.04–1 Hz). These oscillations were in turn band pass filtered out of $f_c[k]$ with FIR filters of length 401 and stop band attenuation of -40 dB. Correlation between the five pairs of band-pass filtered signals were calculated using a window of length 200 s, moving with 100 s steps. Finally, averages of maximum values of each 10 steps were determined (Fig. 4(b).

RESULTS

Examples of mean frequency $f_c[k]$ are shown in Fig. 1. The results of quantification of sleep depth oscillations are depicted in Fig. 2. The oscillations were found throughout the sleep. The mean amplitudes $\pm$ standard deviations in the frequency bands B_1, B_2, B_3 were 0.10 ± 0.06, 0.09 ± 0.04, 0.10 ± 0.03 Hz in SWS, 0.13 ± 0.08, 0.13 ± 0.06, 0.13 ± 0.04 Hz in S2, and 0.16 ± 0.08, 0.15 ± 0.06, 0.13 ± 0.04 Hz in REM.

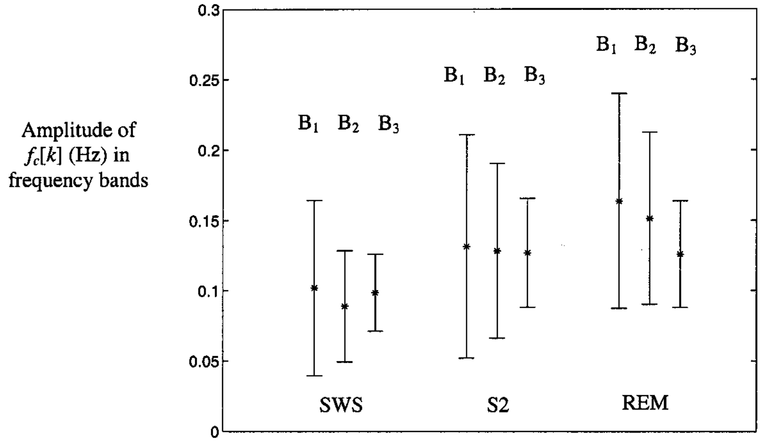

Fig. 2. $N = 15$. Amplitudes of sleep depth oscillations in different frequency bands B_1, B_2, B_3 during SWS, S2, and REM sleep. The mean values are indicated with an asterisk together with bars showing standard deviations. The amplitude in frequency band B_3 is interestingly reduced in REM sleep as compared to other bands.

Interestingly, in REM the amplitude on B_3 was clearly lower compared to the other bands, indicating that the fastest sleep depth oscillations ($T = 30$–70 s) are reduced during REM sleep.

To relate the amplitude of the slow oscillation to current sleep depth, the $f_c[k]$ was median filtered with a filter of length of 200 s, denoted as $f_{c\_200}[k]$. A rule of thumb is that median filtering with a filter of length L s removes oscillations shorter than L s from the signal. The $f_{c\_200}[k]$ provided a slowly changing baseline of sleep depth. The mean level of $f_{c\_200}[k]$ was 2.7, 3.1, and 4.2 Hz in SWS, S2, and REM and thus in light sleep the mean frequency was high, as intended. The amplitude of slow oscillation in each band B_1, B_2, B_3 was thus about 5% of the baseline of sleep depth. When all these components of sleep depth oscillations are together (Fig. 3(a)–(c) there is quite an oscillation with T from 50 to 150 s as compared to current sleep depth. The fact that the magnitude of the slow osciallations was rather large with respect to current sleep depth may explain something behind the visual sleep stage scoring. If, for example, the base level $f_{c\_200}[k]$ remains constant for 1000 s between S3 and S4, the slow oscillations may well cause the visual RKS staging to alternate between S3 and S4. The amplitudes of the even slower components than those with a period time T of 150 s gradually get larger so that the sleep cycles with T around 5400 s show the largest amplitudes (Fig. 3(a).

The average spectrum during the total sleep time of 379,200 s in the 15 recordings (Fig. 4(a) tells that there are sleep depth oscillations at all slow frequencies starting below 0.001 Hz and there is no clear upper limit to them. The amplitude is the larger the slower the oscillation, quite the slowest is that on NREM-REM cycles. The amplitude of sleep depth oscillations then fades towards higher frequencies. The correlation started to decrease at around $T = 50$ s ($f = 0.02$ Hz) and this very likely indicated the transition point where the true sleep depth oscillations faded out and mainly random noise remained (Fig. 4(b).

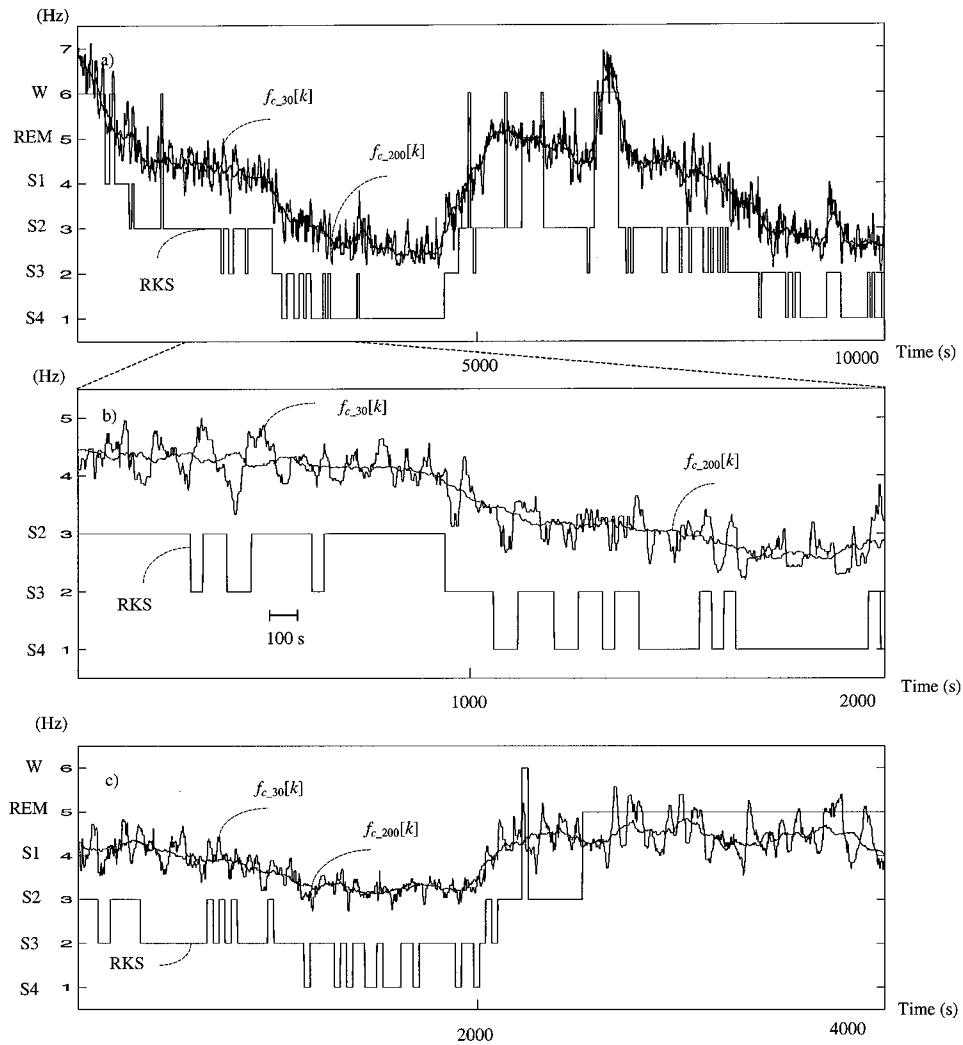

Fig. 3. Examples of sleep depth oscillations. Mean frequency measure $f_c[k]$ after median filtering with a filter of length 30 s (oscillations shorter than $T = 30$ s are removed), denoted as $f_{c\_30}[k]$ and with a filter of length 200 s), denoted as $f_{c\_200}[k]$. The RKS sleep staging is seen in the background. (a) 10000 s in the same recording as in Fig. 1(c). (b) Zoom in 2000 s in the first half. (c) 4000 s in another subject, also REM is seen in this panel. In all cases, there are continuously sleep depth oscillations. The oscillations seen in $f_{c\_30}[k]$) provide additional information of sleep depth as compared to $f_{c\_200}[k]$, which gives a baseline of sleep depth. During REM the sleep depth oscillations appear slower, probably due to reduced amplitude in frequency band B_3.

DISCUSSION

The analysis of the sleep depth oscillations shows the usefulness of computer-based sleep analysis methods. By visual inspection of the original EEG signals, it is virtually impossible to see the existence of these oscillations. In this work, a mean

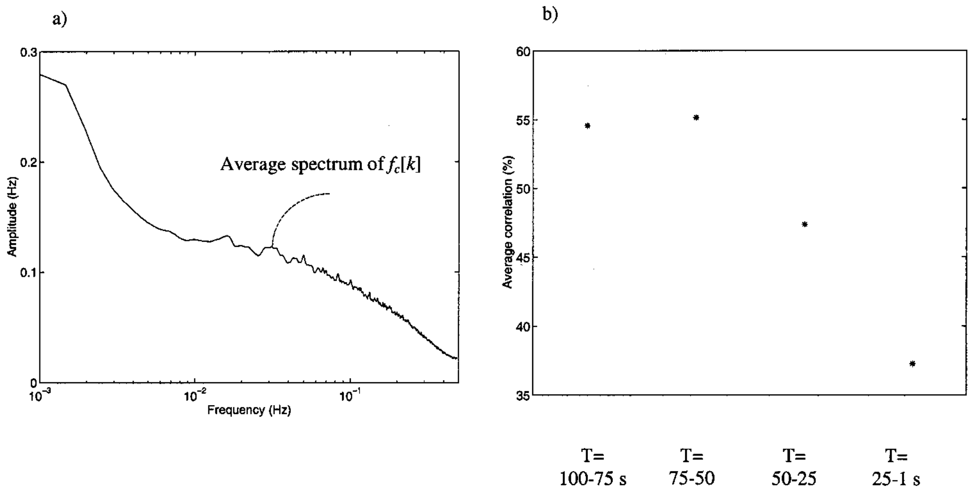

Fig. 4. $N = 15$. Attempt to study the components and noise in $f_c[k]$. (a) Average spectrum of all 15 recordings showing the spectral components of $f_c[k]$. One can see that the slower the oscillation, the larger the amplitude. The quite slowest oscillations are those of sleep cycles, in the order of 0.001 Hz. There is no obvious point where the true sleep depth oscillations end but a knee in the curve can be seen at around 0.02 Hz ($T = 50$ s). (b) Average correlation between signals $f_c[k]$ of symmetric EEg derivations in different bands, indicated on the horizontal axis. The correlation started to decrease clearly at around $T = 50$ s, indicating the probable upper end of sleep depth oscillations, which seems reasonable also on the basis of (a).

frequency measure and FFT and median filtering were used to reveal and quantify these oscillations. The oscillations were continuously present in relatively large amplitude as compared to current sleep depth. As the goal of automated sleep analysis is to provide an accurate picture of sleep process, it would seem that these oscillations should be taken into account in the future systems.

The oscillations with T ranging from 150 to 50 s were quantified in this work to study the fastest components of sleep depth oscillations. Also the fact that slower oscillations would be studied, the more difficult it will be to allocate them to sleep stages, for instance with T of 500 s, an FFT window of length nearly 5000 would be needed. It was assessed in this study that the sleep depth oscillations contain components up to around $T = 50$ s. This finding can be used to design filtering to preserve the true sleep depth oscillations and to remove the noise. The median preserves also the step-wise changes in the underlying signal.(19) The length of a suitable median or alpha-trimmed mean filter is near 30 s. That preserves constant sleep depth oscillations. Detection of transient changes in sleep depth, like EEG arousals,(20,21) will then further complete the analysis of sleep process.

Results of this study confirm that sleep depth does not move directly to deeper sleep and lighter sleep but there is a significant oscillatory motion. It is assumed that thalamic hyperpolarization that is present during sleep(22,23) is involved in this cyclicity. This is the first study to explore this phenomena using data from healty subjects. This work should be continued using additional data, also from subjects suffering from sleep disorders. Studying and understanding these oscillations is one more piece of information to understanding mechanisms of sleep regulation. Automatic sleep analysis systems clearly play a fundamental role in this work.

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