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Systematic performance evaluation of a continuous-scale sleep depth measure

Antti Saastamoinen [a,*], Eero Huupponen [b], Alpo Värri [b], Joel Hasan [a], Sari-Leena Himanen [a]

[a] Pirkanmaa Hospital District, Medical Imaging Centre, Department of Clinical Neurophysiology, P.O. Box 2000, FIN-33521 Tampere, Finland
[b] Tampere University of Technology, Institute of Signal Processing, P.O. Box 553, FIN-33101 Tampere, Finland

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Abstract

In this article, systematic performance evaluation of a continuous-scale sleep depth measure will be discussed. Our main objective has been to select the adjustable analysis parameters such that the best possible correspondence between method output and standard visual sleep staging could be achieved. Sleep depth estimation was based on continuous monitoring of short-time EEG synchronization through the local mean frequency of the EEG. During the experiments, total amount of 752 different combinations of four adjustable parameters were compared based on all-night sleep EEG recordings of 15 healthy subjects. Optimization strategy applied was based on maximizing the weighted average of pair-wise separabilities of EEG mean frequency distributions in all the standard sleep stage pairs. Finally, robustness of the optimized parameters was verified with an independent dataset of 34 all-night sleep recordings.

Our results show that clear topological differences between brain hemispheres and different electrode locations exist. Performance improvements of even 20–30% units can be achieved by proper selection of analysis parameters and the EEG derivation used for the analysis. Remarkable independence of system performance on the analysis window length leads to improved temporal resolution compared to that achieved through standard visual analysis. In addition to giving practical suggestions on the parameter selection, we also propose a possible method for improving stage separability especially between S2 and REM.

Keywords: Sleep depth; Performance evaluation; Computer-based sleep analysis; Computer program

1. Introduction

Clinical assessment of sleep depth has traditionally been based on visual analysis of long-term polysomnography recordings performed in a specially equipped sleep laboratory [1]. In most cases, one successful all-night recording is fully sufficient for clinical diagnostics even though sleep quality may be somewhat disturbed due to unusual sleeping conditions. However, in scientific research it has been rather typical to perform at least two consecutive all-night recordings. The first night is mainly intended for getting the subject accustomed to recording conditions whereas the data recorded during the other nights are used for the actual research work.

During the recordings, relatively large number of signals is recorded. Typically, these include at least several electroencephalography (EEG) traces, eye movements, mental or submental electromyography (EMG), electrocardiography (ECG), different respiratory-related signals (nasal airflow, pressure, respiratory movements of thorax and abdomen, blood oxygen saturation, etc.), and body position. Detailed visual analysis of these recordings gives clinically important information not only on the depth and quality of sleep but also on the possible respiratory, cardiovascular and neurophysiological problems and their interconnections with sleep.

* Corresponding author at: Pirkanmaa Hospital District, Medical Imaging Centre, Department of Clinical Neurophysiology, Teiskontie 35, FIN-33520 Tampere, Finland. Tel.: +358 3 3116 5095; fax: +358 3 3116 4352.
E-mail address: antti.saastamoinen@pshp.fi (A. Saastamoinen).

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In most cases, recordings clearly differentiate between different types of sleep disordered breathing, characterize the incidences and durations of arousals, and give detailed information on other related neurophysiological conditions such as periodic limb movements.

According to the current standard [2], clinical sleep recordings are typically analyzed in consecutive, non-overlapping epochs of either 20 or 30 s of data. Based on certain stage-specific waveforms and interpolation rules during stage changes, each epoch is assigned in one of seven stages consisting of wakefulness, rapid eye movement (REM) sleep, four successively deepening non-REM sleep stages (S1, S2, S3, and S4) and movement time (MT). Standardized visual scoring offers a cost-effective alternative to detailed and therefore laborious and often impractical wave-by-wave visual analysis. However, the advantages gained are often attained at the expense of other inherent inaccuracies of the method [1,3,4]. For example, relatively long epoch duration strongly limits the temporal resolution of the method and may lead to significant loss of clinically important information on short-time wake episodes and stage changes during sleep. Additionally, standard visual scoring method divides continuous sleep process into a small number of discrete stages. For more precise understanding of sleep macrostructure, a continuous-scale estimate of sleep depth with a better temporal resolution would therefore be preferred.

During the recent decades, a multitude of methods aiming at objective, continuous-scale quantification of sleep depth have been presented [3,5,6]. Most of the important early findings of clinical sleep medicine were based on period analysis, which makes it possible to carry out time–frequency analysis even visually for properly band-pass filtered data (for a review, please see [3]). Hjorth parameters were introduced to characterize amplitude, time scale and complexity of the EEG through time-domain operations and were exemplified to be applicable in the analysis of objective sleep depth [7]. More recently, at least stochastic complexity measures [8], relations of certain spectral bands [9–11], models on EEG microcontinuity [12], Hidden Markov Models [13], and segmentation approaches [14] have been applied.

In this article, we discuss performance evaluation of yet another computer-based method for continuous-scale sleep depth estimation. It is based on continuous monitoring of short-time EEG synchronization through EEG mean frequency computed inside a certain frequency band [5,7,15–17]. Main objective of the present work was to select all the adjustable parameters of the method in such a way that the best possible correspondence between method output and standard visual scoring could be achieved. To reach this goal, an optimization strategy maximizing the weighted average of pair-wise separabilities of EEG mean frequency distributions in all the standard sleep stage pairs was applied. Finally, robustness of the optimized parameters was verified with an independent dataset of 34 all-night sleep recordings.

2. Methods

2.1. EEG recordings

The sleep recordings used for parameter optimization consisted of a subset from a large pool of recordings acquired during an EU funded project [18]. All the subjects gave their written consent to participate in the study and the ethical committees of all the recording partners approved the use of the recordings for scientific research. The data were stored at 200 Hz in European Data Format [19] and the recordings were performed after an adaptation night to sleep laboratory conditions. Duration of each recording was about 8 h summing into total amount of 121 h and 52 min of data.

All the included 15 sleep studies were recorded from healthy volunteers, free from any sleep complaints or excessive daytime sleepiness (for details, please see Table 1). Median age of the subjects (7 males, 8 females) was 44 years

Table 1
Individual sleep parameters for all the subjects

Subject	Age	Gender	Total time analyzed (min)	Sleep period (min)	Wake after sleep onset (min)	Total sleep time (min)	Sleep latency (min)	Sleep efficiency (%)
1	47	M	479.0	473.0	32.0	441.0	6.0	92.1
2	43	F	483.0	444.0	8.5	435.5	39.0	90.2
3	44	M	484.5	481.0	48.5	432.5	3.5	89.3
4	52	F	476.0	473.5	7.0	466.5	2.5	98.0
5	63	F	487.5	481.0	58.5	422.5	6.5	86.7
6	49	F	489.5	466.5	15.0	451.5	23.0	92.2
7	37	M	502.5	462.0	53.5	408.5	40.5	81.3
8	22	F	512.0	489.5	56.5	433.0	22.5	84.6
9	59	F	488.0	465.5	94.5	371.0	22.5	76.0
10	24	M	509.5	505.0	40.0	465.0	4.5	91.3
11	22	M	510.5	503.5	61.5	442.0	7.0	86.6
12	46	F	480.0	468.0	87.0	381.0	12.0	79.4
13	28	M	479.0	463.5	40.0	423.5	15.5	88.4
14	49	M	479.5	462.0	37.5	424.5	17.5	88.5
15	43	F	420.0	411.0	12.0	399.0	9.0	95.0

Sleep latency defined as time to the first 60 s of sleep.