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Automatic sleep stage classification using two-channel electro-oculography

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Abstract

An automatic method for the classification of wakefulness and sleep stages SREM, S1, S2 and SWS was developed based on our two previous studies. The method is based on a two-channel electro-oculography (EOG) referenced to the left mastoid (M1). Synchronous electroencephalographic (EEG) activity in S2 and SWS was detected by calculating cross-correlation and peak-to-peak amplitude difference in the 0.5–6 Hz band between the two EOG channels. An automatic slow eye-movement (SEM) estimation was used to indicate wakefulness, SREM and S1. Beta power 18–30 Hz and alpha power 8–12 Hz was also used for wakefulness detection. Synchronous 1.5–6 Hz EEG activity and absence of large eye movements was used for S1 separation from SREM. Simple smoothing rules were also applied. Sleep EEG, EOG and EMG were recorded from 265 subjects. The system was tuned using data from 132 training subjects and then applied to data from 131 validation subjects that were different to the training subjects. Cohen's Kappa between the visual and the developed new automatic scoring in separating 30 s wakefulness, SREM, S1, S2 and SWS epochs was substantial 0.62 with epoch by epoch agreement of 72%. With automatic subject specific alpha thresholds for offline applications results improved to 0.63 and 73%. The automatic method can be further developed and applied for ambulatory sleep recordings by using only four disposable, self-adhesive and self-applicable electrodes.

Keywords: Sleep; Sleep scoring; Sleep stage; Electro-oculography; Ambulatory; Analysis; Automatic; Automated; Computerized

1. Introduction

Traditionally sleep is monitored using a polysomnography with EEG, EOG, EMG and ECG electrodes (Penzel and Conradt, 2000). Especially in ambulatory use, the limiting aspects of the polysomnography include the use of scalp electrodes and the manual scoring of recordings. The scalp electrode placement is more complicated than the use of self-applicable disposable electrodes on areas outside the hairline.

Recording of the sleep stage is important for clinical diagnosis and treatment of sleep disorders (Carskadon and Rechtschaffen, 2005). In the standard approach, sleep is visually segmented into 30 s epochs of wakefulness (W), movement time (MT), sleep stages SREM, S1, S2, S3 and S4 based on features of EEG, EOG and EMG (Rechtschaffen and Kales, 1968). The main information used is the appearance and quantity (density) of certain features within epochs. Standard sleep scoring is a time consuming manual process requiring central scalp electrode, two EOG electrodes, an EMG electrode pair, a reference electrode and a ground electrode (Rechtschaffen and Kales, 1968). Recently modifications have been suggested for standard rules (Iber et al., 2007; Silber et al., 2007).

There is a demand for easily applied automatic methods which could be used in clinical and experimental ambulatory studies and, for instance, for studying the role of sleep duration and quality in the ethiology of metabolic disorders (Knutson et al., 2007). Placement of electrodes outside the hairline would enable the use of self-adhesive electrodes, which could be a self-applicable task (Ehlert et al., 1998; Poree et al., 2006).

The automatic sleep stage scoring using only a two-channel EOG was developed and compared to the standard visual scoring based on EEG, EOG and EMG by using the sleep data of 263 subjects. Algorithms used in our previous studies for the automatic detection of slow wave sleep (Virkkala et al.,

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2007a) and for unintentional sleep onset detection (Virkkala et al., 2007b) were combined and extended for separating wakefulness, SREM, S1, S2 and SWS. Extensions included also simple smoothing rules of sleep stages (Baumgart-Schmitt et al., 1998) and automatic subject specific alpha threshold for offline applications.

2. Materials and methods

The study design has been reported in detail earlier by Härmä et al. (2002). The cross-sectional, population-based, random sample study was approved beforehand by the local ethics committee. A total of 265 randomly selected train drivers and railway traffic controllers were recorded for a single night. Polysomnographic recordings were sorted by the amount of visually scored slow wave sleep (SWS). From the sorted list, entries with an odd order number were assigned to the training group and entries with even order number were assigned to the validation group. The subjects and recordings are identical to our previous study, where only slow wave sleep was analysed (Virkkala et al., 2007a). The mean age of subjects was 43 in the training group and 44 in the validation group. Two subjects, one in the training and one in the validation group, had EOG electrode artefacts for a whole night and were excluded from all analyses.

The recording equipment included a digital 16-channel Embla A10 (Medcare Flaga, Reyakjavik, Iceland) with a sampling rate of 200 Hz and a bandwidth of 0.5–90 Hz. The visual scoring of the recordings was done based on recorded EOG L-M1, EOG R-M1, C3-M2, O1-M2, and submental EMG. The study employed the standard EOG locations: EOG Left (EOG L) slightly lateral and 1 cm up from the outer canthus and EOG right (EOG R) slightly lateral and 1 cm down from the outer canthus referenced to left mastoid M1 (Rechtschaffen and Kales, 1968). A ground electrode was placed on the forehead. The scoring was done by an experienced sleep technologist according to the standard criteria (Rechtschaffen and Kales, 1968). In this study, movement time (MT) was classified as wakefulness (W), and sleep stages 3 and 4 were called slow wave sleep (SWS). The recordings of every tenth subject in the sorted validation list were rescored by another experienced sleep technologist to obtain inter-scorer agreement. For the automatic analysis, only the channels EOG L-M1, EOG R-M1 and the calculated EOG L–R were used.

Similarly to our previous studies, the analysis was run in 0.5 s steps (Virkkala et al., 2007a,b). Two-second Hann-windowed segments were used, which resulted in a 75% overlap. The segments were filtered using a discrete Fourier transform (DFT) and an inverse discrete Fourier transform (IDFT) from 0.5 to 6, 1 to 6 and 1.5 to 6 Hz. In each segment the cross-correlation between the filtered channels EOG L-M1, EOG R-M1 and peak-to-peak amplitude differences from EOG L–R were calculated. The difference between the cross-correlation of the 1–6 Hz band and the cross-correlation of the 0.5–6 Hz band was used as an indicator of slow eye movements (Virkkala et al., 2007b). If eye-movements recorded by EOG are restricted to the 0.5 Hz band and have an opposite phase, this difference is close to 1, and

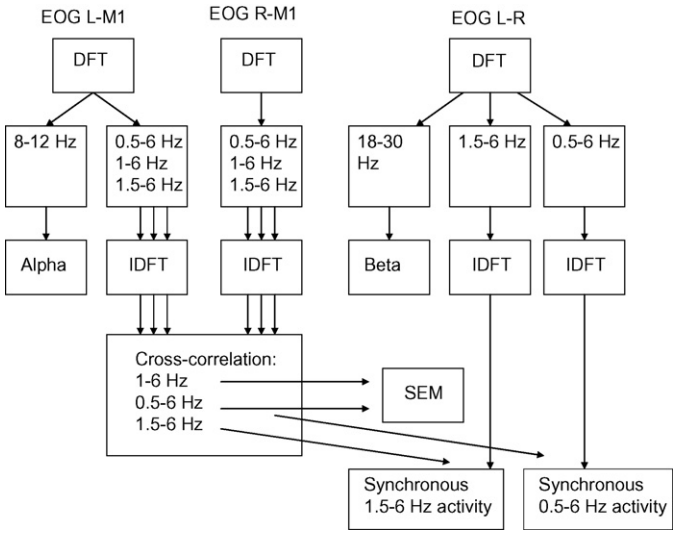

Fig. 1. Description of the algorithm data flow and basic analysis steps. DFT indicates the discrete Fourier transform and IDFT the inverse discrete Fourier transform. Alpha power is obtained by summing the 8–12 Hz bins of the DFT of EOG L-M1. Beta power is obtained by summing the 18–30 Hz bins of DFT of EOG L–R. Synchronized activity is calculated in 0.5–6 Hz and in 1.5–6 Hz bands.

if in addition there is synchronous activity in the 1–6 Hz band, the difference is close to 2. If eye movements are restricted to the 1–6 Hz band and have an opposite phase without any other activity, this difference is close to −1. This slow eye-movement feature is amplitude independent in noise-free measurements.

Alpha power was calculated from the 8 to 12 Hz band from the DFT power spectrum of EOG L-M1. Beta power was calculated from the 18 to 30 Hz band from the DFT power spectrum of EOG L–R. The data flow and basic analysis steps are described in Fig. 1.

Automatic sleep stage classification was done in a hierarchical manner (Fig. 2) and was based on calculating the density of features SW_2, SW_3, S and S_1 indicating the activities of sleep stages S2 or SWS (SW_2), SWS (SW_3), any sleep (S) and

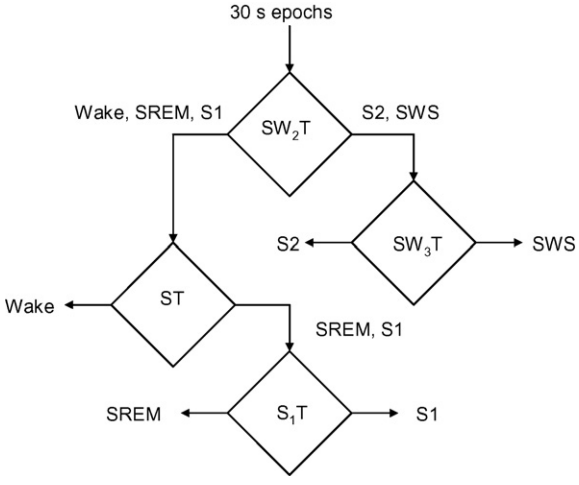

Fig. 2. Decision tree. Four binary decisions rules SW_2T, SW_3T, ST and S_1T were used to separate S2, SWS, wakefulness, SREM and S1.