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Performance of the frequency domain indices with respect to sleep staging

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HIGHLIGHTS

- This work provides detailed comparisons of automatic frequency domain analyses of heart rate variability (HRV), body acceleration, electrooculogram, electromyogram, and electroencephalogram with standard manual sleep staging.
- The spectral parameters of electroencephalogram perform well in identifying sleep, sleep with sleep spindles, and slow wave sleep.
- The frequency domain measures of the electromyogram, HRV, and body acceleration offer high agreement only when differentiating between wakefulness and sleep.

ABSTRACT

Objective: To compare computerized staging using spectral analyses of various electrophysiological signals with manual sleep staging.
Methods: Sleep recordings from 21 normal subjects were scored by an experienced rater and by a dichotomous algorithm. The performance of the spectral indices was assessed by the largest kappa value (LKV).
Results: Theta/beta power ratio of the electroencephalogram, high frequency power (8–58 Hz) of the electromyogram (PEMG), mean R–R interval, and total power (0–16 Hz) of the body acceleration (PACCE) had high (>0.5) LKVs when differentiating between waking and sleep. To differentiate sleep with (stage 2 and slow wave sleep) and without (rapid eye movement and stage 1 sleep) spindles, sigma/beta power ratio had high LKVs. PEMG had a medium (>0.25) LKV to separate rapid eye movement from stage 1 sleep whereas delta/beta power ratio had a high LKV to separate stage 2 and slow wave sleep.
Conclusion: The frequency components of electroencephalogram perform well in identifying sleep, sleep with spindles, and slow wave sleep. Electromyogram, heart rate, and body acceleration offer high agreement only when differentiating between wakefulness and sleep.
Significance: The human–machine agreement is acceptable with spectral parameters, but heart rate and body acceleration still cannot substitute for electroencephalogram.

1. Introduction

The sleep staging system developed by Rechtschaffen and Kales (R&K) (Rechtschaffen and Kales, 1968; Iber et al., 2007; Campbell, 2009) utilizes electroencephalogram (EEG), electrooculogram (EOG) and electromyogram (EMG) to classify the consciousness state into waking, non-rapid eye movement (NREM, including stages 1–4) sleep, and rapid eye movement (REM) sleep. Originally these physiological signals were plotted simultaneously on a chart recorder, and each page (epoch) contained 30 s of data tracings (Rechtschaffen and Kales, 1968; Iber et al., 2007; Campbell, 2009; Merica and Blois, 1997). These tracings were then visually inspected by an experienced rater, and each epoch was scored as a specific stage according to pre-defined criteria. This sleep staging system works stably in a clinical situation. The inter-rater reliability, as defined by the kappa statistic, between two qualified raters can be as high as 0.8 (Berthomier et al., 2007). Although a recently revised version of the R&K criteria has been proposed by the American Academy of Sleep Medicine, the R&K staging system as it was originally proposed has been used as the standardized system for sleep staging for decades (Iber et al., 2007).

The technologies available to record and analyze sleep data have progressed greatly over the past decade. For signal

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recording, ambulatory recordings have become more and more popular; in such cases diverse signals are gathered in a digital format. For example, the size of a newly-developed sleep recorder has been reduced to as small as a matchbox (Kuo and Yang, 2009). The recorder has the capacity to record not only the biosignals required for R&K scoring but also electrocardiogram (ECG) and body acceleration signals, which are now frequently used in sleep research (Yang et al., 2002; Lin et al., 2011; Jean-Louis et al., 2001). For signal analysis, frequency domain analysis has been introduced to assist the visual scoring of sleep data and to analyze variations in the frequency components of sleep data (Campbell, 2009). One question that remains with regard to the newly added signals is how these signals should be processed and whether the resulting indices provide reliable power when carrying out sleep staging (Campbell, 2009; Penzel and Conradt, 2000). Even for the conventional signals, such as EEG, EOG, and EMG, frequency domain analysis can give alternative interpretations (Kuo and Yang, 2009). Among these enormous parameters, we would like to ask at first what the most effective parameters for sleep staging are. With the most effective parameters, we can further determine how well the computerized scoring performs with respect to the R&K sleep staging system.

Using frequency domain analysis performed with EEG, EOG, EMG, and two additional signals, heart rate variability (HRV) and body acceleration, the present study aimed to test the compatibility of these signals with the standard R&K scoring results. More specifically this study firstly investigated various appropriate frequency domain indices, including ratios, to differentiate the pairs of specific sleep/wake states that had been defined by the standard visual scoring, such as between awake and sleep and secondly validated the performance of these frequency domain indices with respect to partial or complete sleep staging.

2. Materials and methods

2.1. Subjects

Nine women and 12 men, aged 22.67 ± 5.00 and 21.33 ± 2.27 (mean ± SD) years old respectively, participated in this study. They were volunteers recruited from a university student population. We interviewed every subject, and all were in good health with regular sleep patterns. There was no evidence of hypnotic drug abuse or above-average alcohol, caffeine or nicotine consumption. None had a history of psychopathology or any medical condition known to influence sleep or the autonomic nervous system (ANS). All subjects gave written informed consent after the experimental procedures were described to them. The procedures used in this study were approved by the Institutional Review Board of National Yang-Ming University.

2.2. Data recording

The electrophysiological signals were recorded by a miniature physiological signal recorder (TD1, Taiwan Telemedicine Device Company, Taiwan) (Kuo and Yang, 2009). This small size (5.2 × 3.1 × 1.2 cm) and light weight (11 g) recorder, was fixed to the subject's chest wall (Fig. 1) and they were designed to acquire sufficient signals for R&K staging with minimal inconvenience to the users. The recordings started from 10 pm and lasted for 24 h, and the subject was allowed to undertake normal daily activity except for vigorous physical exercise and they slept at their homes. The recording was a simplified version of standard sleep monitoring (Rechtschaffen and Kales, 1968), and included EEG, EOG, EMG, ECG and 3-axis acceleration signals. Two one-channel bipolar EEG montages were used, namely C3/Fz (five males and three females) and P3/Cz (seven males and six females). Each subject was recorded

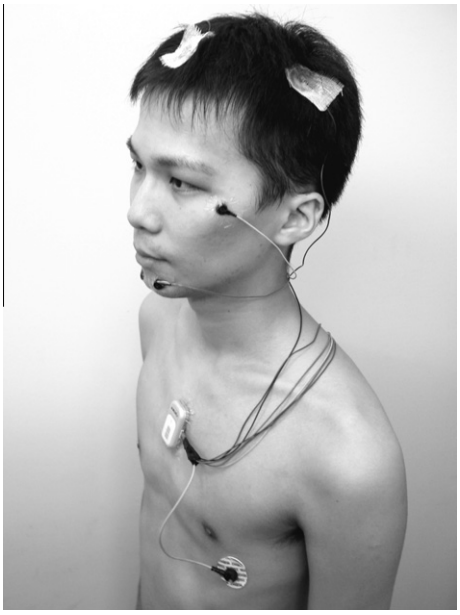

Fig. 1. Picture of the miniature recorder and its position on the body. The recorder is capable of continuously recording electroencephalogram, electrooculogram, electromyogram, electrocardiogram, and three-dimensional accelerations for 24 h. Also shown are its cables and electrodes.

using one EEG montage. EOG was recorded from a pair of differential electrodes placed 1 cm above right outer canthus and 1 cm below left outer canthus (Rechtschaffen and Kales, 1968). EMG was recorded from a pair of differential electrodes on the submental area. ECG was recorded from the V5 site. The 3-axis accelerations were acquired by three individual recording channels (*X*, *Y*, and *Z*), each of which was able to detect accelerations from −3 G (gravity) to +3 G.

The EEG, EOG, EMG, ECG, and 3-axis accelerations were amplified 2000, 1000, 1000, 250, and 1-fold, respectively (Kuo and Yang, 2009). The EEG was filtered at 0.34–53 Hz, the EOG at 0.034–53 Hz, the EMG at 16–113 Hz, the ECG at 1.6–113 Hz, and the accelerations at 0–10 Hz (Kuo and Yang, 2009). The skewness of the filters was 6 dB/octave. Finally the EEG, EOG, EMG, ECG, and 3-axis accelerations were synchronously digitized with a resolution of 12 bit but with different sampling rates (125, 125, 250, 500, and 62.5 Hz, respectively) (Kuo and Yang, 2009). The acquired datasets were stored on a flash memory for subsequent off-line analysis.

2.3. Signal processing

For the frequency domain analyses of EEG, EOG, EMG, HRV, and 3-axis accelerations, we designed a special computer program in Pascal language (Borland Pascal 7.0, Borland, USA). Preprocessing of the ECG signals was designed according to the recommended procedures (Task Force of the European Society of Cardiology and the North American Society of Pacing and Electrophysiology, 1996) as detailed in our previous investigations (Kuo et al., 1999; Yang et al., 2002). In brief, the computer algorithm identified each QRS complex and rejected each ventricular premature complex or noise according to its likelihood in a standard QRS template. Stationary R–R intervals (RR) were resampled and linearly interpolated at a rate of 68.27 Hz to provide continuity in the time domain. A vector magnitude of the 3-axis accelerations (ACCE) was calculated as $\sqrt{(X^2 + Y^2 + Z^2)}$ (Lin et al., 2011) and was resampled at a rate of 34.13 Hz. The sampling rates of the EEG, EOG, and EMG signals were respectively reduced to 68.27, 68.27, and 136.53 Hz by averaging.