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Assessing severity of obstructive sleep apnea by fractal dimension sequence analysis of sleep EEG

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ABSTRACT

Different sleep stages are associated with distinct dynamical patterns in EEG signals. In this article, we explored the relationship between the sleep architecture and fractal dimension (FD) of sleep EEG. In particular, we applied the FD analysis to the sleep EEG of patients with obstructive sleep apnea–hypopnea syndrome (OSAHS), which is characterized by recurrent oxyhemoglobin desaturation and arousals from sleep, a disease which received increasing public attention due to its significant potential impact on health. We showed that the variation of FD reflects the macrostructure of sleep. Furthermore, the fast fluctuation of FD, as measured by the zero-crossing rate of detrended FD (zDFD), is a useful indicator of sleep disturbance, and therefore, correlates with apnea–hypopnea index (AHI), and hourly number of blood oxygen saturation (SpO_2) decreases greater than 4%, as obstructive apnea/hypopnea disturbs sleep architecture. For practical purpose, a modified index combining zDFD of EEG and body mass index (BMI) may be useful for evaluating the severity of OSAHS symptoms.

1. Introduction

Obstructive sleep apnea–hypopnea syndrome (OSAHS) is the most common type of sleep-disordered breathing characterized by recurrent episodes of partial or complete upper airway obstruction during sleep, i.e., the airflow decreases (hypopnea) or is completely interrupted (apnea) despite respiratory effort. There was evidence that untreated OSAHS could increase not only the risk of hypertension, heart attack, stroke, and diabetes, but also the chance of having work-related or driving accidents [1]. According to recent epidemiological studies, nearly 20% of people suffer from OSAHS [2–4]. Moreover the incidences of OSAHS are increasing [5].

Clinically, the polysomnography (PSG), which records a variety of physiologic signals during sleep, such as the electrical activities of the brain, eye movements, muscle activities, heart rates, respiratory efforts, air flow, and blood oxygen levels, is commonly used to diagnose sleep apnea and to determine its severity. The polysomnography derived apnea/hypopnea index (AHI), which counts the number of apneas/hypopneas event per hour, provides a reasonable way to evaluate the severity of OSAHS. According to the clinical guideline, OSAHS is divided into mild, moderate and severe, based on the AHI [6].

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Table 1
The severity distributions of subjects in groups.

Severity	Number of subjects	Mean AHI (/h)	AHI range (/h)
Simple snoring	7	2.27	$0 \le AHI < 5$
MILD	20	9.49	$5 \le AHI < 15$
MODERATE	13	23.03	$15 \le AHI < 30$
SEVER	40	59.73	$AHI \ge 30$

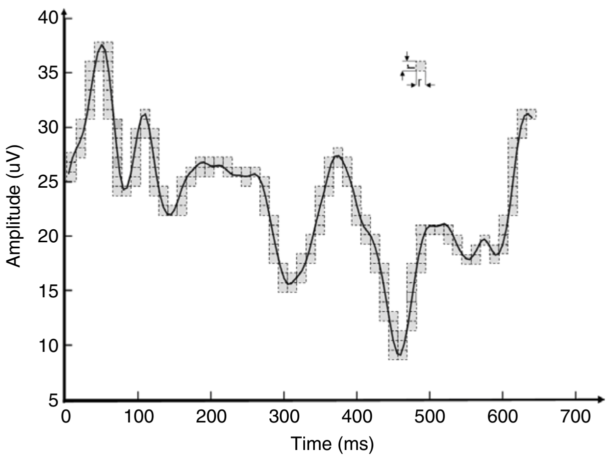

Fig. 1. Illustration of the box-counting algorithm. The number of covering boxes varied with different box side lengths of r, and fractal dimension is calculated by $FD = -\lim_{r\to 0} \frac{\log_2[N(r)]}{\log_2(r)}$.

Recent studies showed that patients with OSAHS could exhibit different disruptions in sleep macro-architecture [7]. Methods based on the quantifications of dynamic properties of physiological signals, such as the Hurst exponent, correlation dimension and Lyapunov exponent analyses [8], have been applied to analyze sleep Electroencephalogram (EEG). These methods have been shown to be useful in describing sleep architecture. In this study, we decide to investigate the utility of applying fractal dimension (FD) analysis to sleep EEG to extract the sleep macro-architecture of each subject and find a new descriptor to quantify the disruption in the macro-architecture of sleep. Furthermore, the temporal fluctuation of the local FD (as measured within a 30-s moving window) time series should provide an indication of how disruptive the sleep is, and, therefore, may provide useful information about the severity of OSAHS.

2. Subjects and data

The sleep EEG of 80 patients (mean age 48.5 ± 14.2 years, range 19–82 years, 16 females and 64 males) with different levels of severity of OSAHS was analyzed retrospectively. The whole night polysomnographic data were attained from the Sleep Laboratory of Department of Pumimonary Medicine of Peking University First Hospital (Siesta Wireless Sleep Monitoring System, manufactured by Compumedics. Ltd., Australia). For each subject, sleep stages and apnea episodes were determined based on the annotation of multi-channel signals including EEG, ECG, electro-oculogram (EOG), SpO_2, airflow, thorax efforts, abdominal efforts, snoring sound, leg movement, and body position, with respect to sleep stages and apnea. EEG signals Analyzed were from the C3 derivation with a sampling rate of 128 Hz. The sleep stages were visually scored for each 30-s epoch by experienced clinical staffs, according to the 2007 AASM (American Academy of Sleep Medicine) sleep scoring manual. Groups of subjects with different levels of severity of OSAHS are summarized in Table 1.

3. Fractal dimension measurement of EEG

Fractal dimension (FD) was originally introduced as a description of self-similar objects [9] and subsequently utilized in a variety of scientific disciplines [10–12,27].

The local FD of sleep EEG signals in each 30s' epoch was estimated by a standard "box-counting" algorithm as illustrated in Fig. 1. By covering a structure such as EEG signal with boxes of side length r, the fractal dimension FD is given by

$$FD = -\lim_{r\to 0} \frac{\log_2[N(r)]}{\log_2(r)} \quad (1)$$

where $N(r)$ is number of non-empty boxes needed to completely cover the structure, and FD corresponds to the slope of the plot $\log_2[N(r)]$ versus $\log_2 r$. An FD time series was generated by sequentially moving 30-s window forward in time.