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Heterogeneous recurrence analysis of heartbeat dynamics for the identification of sleep apnea events ☆

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ABSTRACT

Obstructive sleep apnea (OSA) is a common sleep disorder that affects 24% of adult men and 9% of adult women. It occurs due to the occlusion of the upper airway during sleep, thereby leading to a decrease of blood oxygen level that triggers arousals and sleep fragmentation. OSA significantly impacts the quality of sleep and it is known to be responsible for a number of health complications, such as high blood pressure and type 2 diabetes. Traditional diagnosis of OSA relies on polysomnography, which is expensive, time-consuming and inaccessible to the general population. Recent advancement of sensing provides an unprecedented opportunity for the screening of OSA events using single-channel electrocardiogram (ECG). However, existing approaches are limited in their ability to characterize nonlinear dynamics underlying ECG signals. As such, hidden patterns of OSA-altered cardiac electrical activity cannot be fully revealed and understood. This paper presents a new heterogeneous recurrence model to characterize the heart rate variability for the identification of OSA. A nonlinear state space is firstly reconstructed from a time series of RR intervals that are extracted from single-channel ECGs. Further, the state space is recursively partitioned into a hierarchical structure of local recurrence regions. A new fractal representation is designed to efficiently characterize state transitions among segmented sub-regions. Statistical measures are then developed to quantify heterogeneous recurrence patterns. In addition, we integrate classification models with heterogeneous recurrence features to differentiate healthy subjects from OSA patients. Experimental results show that the proposed approach captures heterogeneous recurrence patterns in the transformed space and provides an effective tool to detect OSA using one-lead ECG signals.

1. Introduction

Obstructive sleep apnea (OSA) is a common sleep-related breathing disorder with symptoms of frequent cessation of respiration during sleep. According to Young et al. [1], 24% of adult men and 9% of adult women are impacted by OSA. OSA occurs due to the collapse of upper airway. During normal respiration, the diaphragm produces a negative intrathoracic pressure that pulls fresh air into the lungs. Such process requires the upper airway to be open actively. However, the neural activation of the diaphragm is not at the same pace with dilator muscles that regulate upper airway caliber in OSA patients [2,3]. As such, the negative intrathoracic pressure is not able to inhale airflow, but results in a collapse of the upper airway. As a consequence, breathing pauses for a few seconds, which leads to a decrease of oxygen level and an increase of CO_2 in the blood. It triggers an activation of the central nervous system and results in arousals. The arousal ceases the process of sleep and brings blood oxygen level back to normal by a few breaths. According to Penzel et al. [2], a patient with OSA may experience up to 600 apneas (i.e., breathing pauses) per night. This significantly impacts the quality of sleep and results in daytime drowsiness, irritability, tiredness, depression, and memory problems.

OSA is a chronic condition that responsible for a growing number of health complications, including high blood pressure, obesity and type 2 diabetes. It is also an independent risk factor for various cardiovascular diseases. For example, people with OSA are more likely to suffer from myocardial infarction during nighttime. This is because the sudden drop of blood oxygen level strains the cardiovascular system and further inhabits the oxygen supply to cardiac muscles. Also, it is estimated that the presence of OSA conferred a greater than 2 increase in the likelihood of having heart failure [4,5]. Effects of OSA on other types of cardiovascular diseases (e.g. arrhythmia and stroke) were reported in [6]. OSA has significant impacts on the personal health and may lead to severe

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short-term and long-term health consequences, and has become a burden for society, family and the individual. Effective detection of OSA is critical to reduce related ailments, control healthcare cost and improve chronic disease management.

In clinical practice, cardiorespiratory polysomnography (PSG) is the gold standard method to detect OSA. During PSG, multichannel bio-signals are recorded during one or more overnight stay, including electrocardiogram (ECG), electroencephalogram (EEG), electromyography (EMG) and electrooculography (EOG). These signals are used to evaluate sleep stages (e.g., awake, REM, N_1, N_2 and N_3). Also, both the amount of airflow through the nose and the movement of chest wall are monitored for estimating respiratory effort. In addition, oxygen saturation (SpO_2) is monitored for evaluating the effect of respiration. Apnea-hypopnea index (AHI) is calculated from PSG records to assess the severity of OSA. A subject with AHI up to 5 is considered as normal and exceeding 5 is diagnosed as OSA. However, it is noteworthy that PSG requires to be conducted in the sleep center with dedicated personnel and equipment. Along with high expense, the limited resource makes PSG not accessible to the general population. Furthermore, PSG impacts normal sleep. It is uncomfortable to attach large amount of sensors on the body and face during PSG. Patients find it difficult to sleep well when wearing sensors and wires in the unfamiliar lab environment. In addition, the calculation of AHI is time consuming and it is often subject to the bias of individual sleep expert. As an alternative, Home Sleep Test (HST) system has been introduced recently for the diagnosis of OSA. There are a variety of HST devices with different sensors, and usually measure the patients' breathing and blood oxygen level during sleep. Some may also measure heart rate and other physiological information about the human body (https://www.sleepassociation.org). Although the cost associated with HST is significantly lower than that of PSG, it still requires patients to wear the devices/sensors on the nose, mouth, chest or abdomen for 1–3 nights, which could potentially affect sleep quality. Besides, just like PSG, HST relies on sleep experts to interpret the data. Hence, there is a pressing need to develop convenient and easy-to-access ways for the detection and evaluation of OSA.

Previous studies have hinted that ECG alone is well suited for the detection and prediction of OSA [7]. During sleep apnea, the cessation of respiratory process reduces blood oxygen level and further affects the function of cardiovascular system. Characterizing disease-induced variability in ECG signals reveals underlying patterns of apneic events. In the literature, researchers have developed methods in time, frequency and phase space domains to explore hidden information from ECG signals for improving the diagnostics of OSA. A comprehensive review of the state of the art is given in Section 2. Advantages of using ECG for the detection of OSA are multifold, including: (1) the acquisition of ECG signals (especially single-lead ECG) is much easier compared with other PSG recordings. Advanced sensing brings the proliferation of portable/ambulatory ECG devices. For example, DiCare m1CP is one of the smallest and lightest ECG recorders. It can monitor the ECG trace continuously for 24 h or longer. Fingertip/chest touch and electrode patch models are available to a portable recording device (http://www.dimetekus.com/). Also, Creative Medical developed a portable ECG device, which supports 10-h continuous monitoring of 1-lead ECG by holding the electrode patches by hands or attaching them to the wrists. Recorded data can be transmitted wirelessly to computers and servers for further analysis (http://www.creative-sz.com/Easy-ECG-Monitor/). (2) ECG features, e.g., RR intervals, are strongly pertinent to the pathological mechanism of OSA events. It has been shown that RR intervals are impacted by OSA-induced parasympathetic and sympathetic cardiac activity [8]. In the end of an OSA event, RR interval becomes shorter and the immediate post-event RR interval diminishes. Therefore, OSA events can be characterized by the disease-induced variations in RR intervals.

However, most existing approaches are limited in their ability to characterize nonlinear dynamics underlying ECG signals. It may be noted that behaviors of complex system are reflected in its dynamics. Whether the system is in the steady state, or undergoes transient and intermittent behaviors, the system dynamics show abrupt changes and reveal complex characteristics such as nonstationarity and recurrences. It is well known that ECG signals contain fundamental information pertinent to behaviors of cardiovascular system. Thus, accurate detection of OSA events hinges on the characterization of disease-induced dynamics underlying ECG signals. Some existing approaches consider homogenous recurrence dynamics of ECG signals for the identification of sleep related breathing disorders [9], but fail to capture variations in the nonlinear and nonstationary properties of OSA-induced dynamics [10,11], in which recurrence states are different because of state properties and evolving system dynamics [12,13]. Therefore, OSA-induced nonlinear dynamics are more concerned with heterogeneous recurrence variations underlying ECG signals. Hence, there is a pressing need to fully exploit heterogeneous recurrence variations and link them with the detection and prediction of OSA events.

In this study, we proposed a novel approach of heterogeneous recurrence analysis [12,13] to fill these gaps. First, we reconstruct a nonlinear state space using a time series of RR intervals that extracted from single-channel ECGs. A new partition scheme was then introduced to recursively partition the state space into a hierarchical structure of local recurrence regions. Second, a fractal representation is designed to efficiently characterize transitions of heterogeneous recurrence states in segmented sub-regions. Third, we develop new statistical measures to quantify heterogeneous recurrences. Fourth, we integrate classification models with heterogeneous recurrence analysis for the detection of OSA events.

The reminder of this paper is organized as follows: Section 2 reviews the state of the art for OSA detection and prediction. Section 3 introduces the methodology designed in this present study. Section 4 and 5 present the material and experimental results, and Section 6 includes the discussion and conclusions arising out of this investigation.

2. Research background

OSA is a chronic condition that impacts a growing population in the US. Effective treatment calls for accurate detection and evaluation of OSA events. In clinical practice, PSG is considered as the gold standard to evaluate the severity of OSA. However, interpretation of PSG records relies heavily on sleep experts. It requires intensive work and often subjects to the bias of individual expert. In the literature, algorithms were developed for computer-aided analysis of PSG records. For example, Várady et al. [14] proposed a method for PSG data processing that focused on thoracic and abdominal excursion signals. Phase differences of these respiration-related signals were analyzed to evaluate the presence and extension of OSA events. As opposed to previous off-line approaches, their method was more efficient and could be used for online monitoring of OSA patients.

However, PSG requires dedicated equipment and careful nursing. It is an expensive and time-consuming procedure, and is not accessible to the general population. In the literature, various methods were developed for out-of-center monitoring of OSA with a reduced number of sensors. For example, the recent advance in sleep apnea study has enabled HST to provide patients with convenience and a more typical night of sleep study in the comfort of their home. HST measures fewer channels than a full PSG, but still