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Original Article

Sleep Apnea Detection from Single-Lead ECG Using Features Based on ECG-Derived Respiration (EDR) Signals

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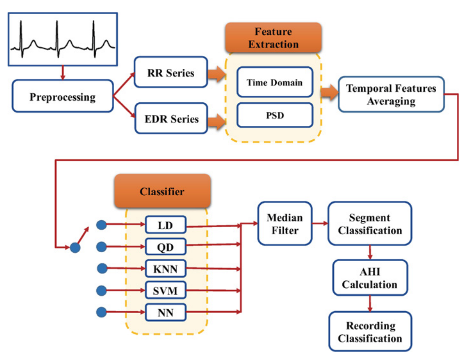
Highlights

- Two new algorithms for extracting ECG-derived respiration (EDR) using single-lead ECG.
- Comparing EDRs to other state-of-the-art EDR in terms of similarity to a reference respiration signal.
- Extraction features from EDRs to be used in an automatic sleep apnea detection algorithm.
- Improving automatic ECG-based sleep apnea detection accuracy.

Graphical abstract



Abstract

Background and objective: One of the important applications of non-invasive respiration monitoring using ECG signal is the detection of obstructive sleep apnea (OSA). ECG-derived respiratory (EDR) signals, contribute to useful information about apnea occurrence. In this paper, two EDR extraction methods are proposed, and their application in automatic OSA detection using single-lead ECG is investigated.

Methods: EDR signals are extracted based on new respiration-related features in ECG beats morphology, such as ECG variance (EDR_{Var}) and phase space reconstruction area (EDR_{PSR}). After evaluating the EDRs by comparing them to a reference respiratory signal, they are used in an automatic OSA detection application. Fantasia and Apnea-ECG database from PhysioNet are used for EDRs assessments and OSA detection, respectively. The final performance of our OSA detection is tested on an independent test data which is also compared with results of other techniques in the literature.

Results: The extracted EDRs, EDR_{Var} and EDR_{PSR} show correlations of 72% and 70% with reference respiration, which outperform the other state-of-the-art EDR methods. After feature extraction from EDRs and RR intervals series, the combination of RR and EDR_{PSR} feature sets achieved 100% accuracy in subject-based apnea detection on independent test data, and also minute-based apnea detection is done with accuracy, sensitivity and specificity of 90.9%, 89.6% and 91.8%, which is better than other automatic algorithms in the literature.

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Conclusions: Our OSA detection system using EDRs features yields better independent test results compared with other state-of-the-art automatic apnea detection methods. The results indicate that ECG-based OSA detection system can classify OSA events with high accuracy and suggest a promising, non-invasive and efficient method for apnea detection.

Keywords: Obstructive sleep apnea; ECG; EDR; Classification; Phase space reconstruction

1. Introduction

Sleep-related breathing disorders (SRBDs) are originated from repetitive interruption of respiration which usually produce sleep arousals, hypoxia, or both. There are different syndromes for SRBD: three of them are obstructive sleep apnea (OSA), central sleep apnea (CSA) and mixed apnea with both obstructive and central syndromes [1]. OSA is caused by the collapse of the airway which is a 10-second or larger pause in respiration activity along with continuing ventilatory effort. Obstructive hypopneas also make decreases in ventilation, but not complete cessation of it and cause a fall in oxygen saturation or arousal. OSA is diagnosed when a patient has an apnea-hypopnea index (AHI; number of apneas and hypopneas per hour of sleep) larger than 5 and shows symptoms such as daytime sleepiness. CSA is determined by repeated cessation of respiration during sleep resulting from the loss of ventilatory drive that causes a 10-second or larger pause in ventilation with no respiratory effort [2]. Mixed sleep apnea is the combination of both CSA and OSA events. Among the three different forms of sleep apnea (obstructive, central, or mixed), OSA is the most common [3].

Polysomnography (PSG) test is the traditional OSA detection method which requires an all-night analysis in a clinic environment with medical supervision. PSG as the reference standard for diagnosing OSA is a complex diagnostic sleep test that includes at least electroencephalogram (EEG), electromyogram (EMG), electrooculogram (EOG), electrocardiogram (ECG), breathing/respiratory effort, airflow and oxygen saturation (SaO2) recording. PSG is difficult, time-consuming and, at times, out of reach or even impractical [4]. Hence, a simple screening method, which provides a reliable diagnosis of sleep apnea without referring to PSG is of interest.

Abnormal heart activities or high heart rate variability (HRV) can provide evidence of OSA occurrence [5]. Heart rate (HR) is based on the time between two consecutive R-peaks, known as the RR interval. In addition, ECG recording signals convey respiration information that can be derived from ECG which are called ECG-derived respiration (EDR) [6], and using these indirect extracted respiration information can also be useful in OSA diagnosis. Thus, ECG-based screening systems are promising in noninvasive OSA diagnosis. Few studies have addressed sleep apnea detection from ECG until the PhysioNet/Computers in Cardiology Challenge 2000. PhysioNet and the Coordinators of the 2000 Computers in Cardiology (CinC) Conference jointly organized this competition to prove the efficacy of ECG-based methods for sleep apnea detection using a large and representative set of data [7]. PhysioNet is an online library of biomedical signals and open-source software, and its sponsor is US National Institutes of Health's National Centre for Research Resources [8]. Competitors were invited to two challenges: 1) classifying the recordings in the test set with sleep apnea and the normal recordings, 2) labeling each minute in all 35 test recordings as an apnea or non-apnea minute [7]. Accordingly, the steady stream of research articles were published which indicates that there is a connection between sleep apnea and ECG signal. In those researches either, rule-based or learning algorithms are used for apnea detection.

Respiration activity causes some morphological changes in the ECG signal due to some mechanisms, such as: **i)** changes in volume of the lung during inspiration and expiration cycles that leads to fluctuation in electric impedance of thorax, and **ii)** changes in the heart vector position with respect to ECG electrodes [9]. According to these morphological changes caused by respiration effects on recorded ECG signal, respiratory information or EDR signal can be extracted from ECG using some signal processing techniques.

Most of ECG-based OSA detection algorithms in the literature have used different ECG-derived parameters related to respiration (EDR signals) and HRV signal to extract time domain, frequency domain and other nonlinear features. They have used these features as inputs of the black-box decision making process and classifiers. The top-three algorithms participated in PhysioNet/CinC Challenge 2000 used time and frequency domain features of HRV or EDR signals that could classify all 30 test subjects correctly and were the top-scoring algorithms (up to 89.4% accuracy) in the minute-by-minute apnea detection [10–12]. Apart from the winner that used visual classification procedure [10], the other two participants automatically detected apnea events. In addition, each method used different EDR extraction algorithms based on morphology of ECG beats, because changes in respiration activity affect the ECG morphology [7]. EDR signals are generated by measurements of the T-wave amplitude [10], S-wave amplitude [11] or R amplitude [12]. In another study, a variety of features are extracted from HRV and the EDR signal obtained by sampling the area enclosed by QRS waves (EDR_{Area}), and the performance of classifiers, such as linear and quadratic discriminants were compared [13]. In [14], minute-by-minute apnea detection is provided using features derived from R-peak amplitude series as an EDR sample series (EDR_{Ramp}). Some other studies used wavelet-based features from EDR_{Ramp} or EDR_{Area} and HRV for automatic recognition of patients with OSA [15,16]. Time and frequency domain features were obtained from RR intervals and EDR based on QRS area in [17] and minute-by-