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Modified thoracic impedance plethysmography to monitor sleep apnea syndromes☆

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Abstract

Background and purpose: In order to identify sleep disorders by thoracic impedance plethysmography (TIP), we propose several new techniques: the application of an adaptive filter, a scaled Fourier linear combiner (SFLC) to eliminate cardiac-derived fluctuation in the impedance waveform, and the use of heart rate variability (HRV) to ascertain whether the airflow is obstructed.

Patients and methods: Laboratory simulation experiments on four healthy individuals and actual overnight measurements on five patients with sleep disorders were carried out. Amplified thoracic impedance change (ΔZ), ECG, a phonocardiograph, a pneumotachograph and a standard polysomnograph were recorded. The SFLC was applied to ΔZ to selectively extract the cardiac-synchronous component (ΔZ_{CSC}), and the remainder of the waveform (ΔZ_{REM}) was low-pass filtered to estimate the waveform driven by respiration. The HRV was divided into respiratory synchronous (HRV_R) and low frequency (HRV_L) components.

Results: The SFLC could drastically extract ΔZ_{CSC} from ΔZ and thereby demonstrate a ΔZ_{REM} pattern quite similar to the flow–volume curve of the pneumotachograph. Central sleep apnea could be identified as the cessation of ΔZ_{REM} and concomitant attenuation of HRV_R. Obstructive sleep apnea could be identified as the maintenance of rhythmic but attenuated variations of ΔZ_{REM} accompanied by asynchronous fluctuation of HRV_R against ΔZ_{REM}. Central hypopnea could be identified as a normal but attenuated waveform in both ΔZ_{REM} and HRV_R. A large fluctuation in HRV_L was observed during repetitive appearances of apnea/hypopnea in the nocturnal experiments.

Conclusion: The modified TIP together with HRV provides a superior tool for accurate and convenient definition of sleep apnea syndromes.

Keywords: Thoracic impedance plethysmography (TIP); Sleep apnea syndrome (SAS); Central sleep apnea (CSA); Obstructive sleep apnea (OSA); The scaled Fourier linear combiner (SFLC); Heart rate variability (HRV)

1. Introduction

Sleep apnea syndrome (SAS), a sleep-related breathing disorder, is not only a co-morbid condition in itself but also a risk factor for cardiovascular diseases and work-related accidents [1–3]. Because the latent morbidity of SAS in middle-aged and older men has been estimated to exceed 4%, diagnosis and treatment of SAS is now a great concern in national health promotion or occupational health [4,5]. Generally, SASs have been classified into several types, including central sleep apnea (CSA), obstructive sleep apnea (OSA), central hypopnea and obstructive hypopnea, using standard polysomnography, which includes electrocardiograph, electroencephalograph, electro-oculograph, chin electromyograph, and pulse oximeter, respiratory flow and effort, in the sleep laboratory [6]. One of the problems in obtaining these measurements is how to accurately measure respiratory flow and effort without

☆ The simulation experiment was carried out at the Toyohashi University of Technology, and the nocturnal measurements of patients at the Toyohashi Mates Clinic.

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discomfort to the patient [6,7]. The pneumotachograph is the reference standard to measure respiratory flow, but its attachment may produce sleeplessness or discomfort. Hence, the most popular tool for airflow measurement is the thermosensor, but this method is still unreliable in quantitative measurement [6,7]. Thoracic impedance plethysmography (TIP) had also been used as a convenient monitor of respiration since middle of the last century [8,9]; however, recent studies using TIP for sleep disorders have revealed several drawbacks [9,10]. Brouillette et al. [10] reported three typical misinterpretations when using TIP. First, cardiac-induced variations in the impedance waveform are occasionally misinterpreted as breath. Second, TIP misinterprets OSA as breath because the impedance waveform fluctuates in accordance with respiratory muscle movements during OSA. Third, TIP cannot detect breaths following a sigh because the impedance signal is scaled out by the sigh. Moreover, Larsen et al. [9] pointed out that small and gross body movements interfere with breath detection by TIP. Because of the above drawbacks of TIP and the use of other convenient sensors for airflow detection, TIP has fallen into disuse in the definition of SASs, especially in sleep laboratories. However, TIP has many advantages: it is non-invasive, simple and produces less discomfort, and if these drawbacks can be overcome, TIP may be widely used as an ambulatory monitor in the hospital or at home.

The first problem with using TIP in sleep study is, therefore, how to eliminate the cardiac-derived artifacts in ΔZ pointed out by Brouillette et al. [10]. Wilson et al. [11] proposed analogue and digital filters to eliminate noises caused by cardiac movements, and reported only small but significant improvement in noise elimination was obtained. Recently, Barros et al. [12] developed an adaptive filter, the scaled Fourier linear combiner (SFLC), that can select the components synchronous with the R–R interval of the ECG. If true, the remainder of the impedance waveform must involve mainly components driven by respiration at rest. The first purpose of the present study is, therefore, to validate the ability of the SFLC to eliminate noise driven by cardiac movements in the impedance waveform. This will contribute to the definition of CSA.

The second problem with TIP is the misinterpretation of OSA, because the impedance signal can be changed by respiratory effort despite a cessation of airflow. If the airflow or airway pressure can be measured simultaneously with TIP, OSA may be detected easily. However, as noted above, attachment of a respiratory flow detector or airway pressure sensor may produce discomfort or sleeplessness in patients. Thus, in the present study, the idea of using heart rate variability (HRV) for indirect assessment of respiratory flow is proposed because, as has been clarified by the study of HRV, two major components, the respiratory synchronous and low-frequency components located around 0.1 Hz, were observed in healthy individuals, and the magnitude of the respiratory synchronous component (HRV_R) correlates with tidal volume and is attenuated mostly by the vagal blockade [13–16]. If the airflow is obstructed or the lung is not inflated during OSA, the HRV pattern may be modulated. The second purpose of the present study is to examine the validity of using HRV to accurately distinguish OSA from normal breathing or hypopnea.

Finally, further problems related to using TIP with the definition of SASs are also discussed.

2. Methods

2.1. Protocols

In the present study we designed two experiments. The first was a simulation of voluntary control of breathing to produce conditions corresponding to CSA, OSA and hypopnea by four healthy individuals at supine rest. In the controlled CSA, the subjects intermittently occluded their nose and mouth for 30 s at the end of both expiration and inspiration during normal breathing. In the controlled OSA, the subjects intermittently occluded their nose and mouth as in CSA, but they attempted to inspire and expire consciously by moving their respiratory muscles during this period. In hypopnea, the subjects voluntarily reduced their tidal volume while maintaining their breathing rhythm. During the above experiments, output signals from a thoracic impedance plethysmograph (AI-601G, Nihonohden, Japan), a phonocardiograph (AS-601H, Nihonkohden, Japan), an electrocardiograph (AC-601G, Nihonkohden, Japan) and a pneumotachograph (WFMU-1100, Westron, Japan) were continuously recorded on the digital data recorder (DR-M3, TEAC, Japan). The sampling frequency of all data was set at 200 Hz. The spot electrodes for impedance measurements were placed on the forehead and 3 cm below the navel for current, and at the top of the sternum and the lower edge of the xiphoid process along with the median sagittal line for voltage, respectively.

In the second experiment, thoracic impedance, ECG and phonocardiograph were simultaneously recorded with the standard polysomnograph (Sleepwatcher, Compmedics, Australia) in the clinic throughout the overnight study of five SAS patients to assess the accuracy of the techniques proposed above. The subjects were all men, and their mean age was 54.6 ($\pm$10.6) years. The judgment and classification of SASs were done by referring to the polysomnographic data from the registered polysomnographic technologist in the clinic.

Preceding the study, informed consent was obtained from all subjects, and all experimental procedures conformed to the principles outlined by the Declaration of Helsinki.

2.2. Data processing

An adaptive filter, the scaled Fourier linear combiner (SLFC), was applied to the amplified base impedance