

# Apnea Event Estimation During Sleep Using Polyvinylidene Fluoride Film

Su Hwan Hwang, Hee Nam Yoon, Da Wun Jung and  
Kwang Suk Park

Interdisciplinary Program of Bioengineering  
Seoul National University  
Seoul, Korea  
lostzoo@bmsil.snu.ac.kr

Yu-Jin Lee and Do-Un Jeong

Department of Neuropsychiatry and Center for Sleep and  
Chronobiology  
Seoul National University Hospital  
Seoul, Korea  
eugenie8199@hotmail.com

**Abstract**—This paper suggests an unconstrained method for sleep apnea event detection during sleep based on physiological signal from polyvinylidene fluoride (PVDF) sensor. Sleep apnea syndrome (SAS) is a common sleep-related breathing disorder and it is closely related with cardiovascular diseases. Polysomnography (PSG) is the gold standard for SAS diagnosis but it has many drawbacks. Six SAS patients participated in our study and patient's respiratory signals during sleep were collected by a PVDF sensor which was installed on a bed. Sleep apnea events were detected using amplitude of measured respiration signals and the Apnea Hypopnea Index (AHI) results were compared with those from PSG. The Pearson correlation coefficient between paired results was 0.982 ( $p < 0.001$ ) and apnea severity of each patient was accurately assessed.

**Keywords**—Sleep Apnea; PVDF film; Polysomnography

## I. INTRODUCTION

Sleep apnea is a kind of sleep-related breathing disorders (SRBDs) which is characterized by repetitive abnormal interruption of breathing during sleep. About 4 % of adult men and 2% of adult women suffer from sleep apnea syndrome (SAS) [1]. Since SAS disrupts the sleep architecture of patients, it can lead to systemic hypertension [2], fatigue [3] and heart failure [4]. In addition, previous studies reported that sustained sleep apnea syndrome is associated with cardiovascular diseases [4], such as arrhythmia, ischaemic heart diseases. Continuous monitoring of apnea events during sleep can be a useful tool for the early detection and prevention of sleep apnea-related disorders. It is accompanied by improvement the quality of daily and the reduction of healthcare costs.

In a traditional sleep and sleep-related disorder diagnostic system, polysomnography (PSG) is a representative method. Even though PSG has been regarded as the gold standard to diagnose and monitor SAS, there are some drawbacks. PSG recording during sleep provides a discomforting experience to patient because many electrodes are attached to the patient's face and body. Moreover, it demanded specially trained sleep experts, relatively long set-up time, high costs and a controlled hospital environment.

To overcome these disadvantages, there have been many alternative ways to detect SAS without PSG recoding. In previous studies, the electrocardiogram (ECG)-based method revealed that RR-interval- [5] or R-peak amplitude-based classification method [6] is feasible for apneic epoch

determination. Also, respiratory-based or pulse oximetry-based studies reported high correlation coefficient ( $r > 0.9$ ) between AHI from PSG and suggested ones. Despite these attempts, dominant system for the unconstrained monitoring of sleep apnea still does not exist.

Polyvinylidene fluoride (PVDF) film is a piezoelectric polymer which is good for application where mechanical stress is being applied. This thin and flexible film is widely used for film transducer or speaker elements and specially applied where signal to noise requirements influence very low mass loading by the sensors. In previous studies, PVDF film was used as a sensor for recoding of respiration and heart rate [7] [8]. Although these studies have been made to non-intrusively measure subject's physiological signals, the algorithm for apnea event detection from signals measured by PVDF sensor has rarely been studied.

In this study, we established the unconstrained sleep apnea monitoring system using PVDF sensor and assessed the accuracy of our system compared to PSG.

## II. METHOD

### A. Subjects and PSG data

Six SAS patients participated in our study. According to apnea and hypopnea index (AHI, events per hour), four patients showed severe severity and others were moderate severity. Sleep-related parameters of the patients were summarized in Table 1. Nocturnal PSG was conducted at Center for Sleep and Chronobiology, Seoul National University Hospital (SNUH). Patient's PSG data were scored according to the guideline of R&K by registered polysomnographic physicians [9]. This procedure was approved by the institutional review board of SNUH, Seoul, Korea.

TABLE I. SLEEP-RELATED PARAMETERS OF PATIENTS

Parameter	Value (mean $\pm$ S.D.)
Gender (Male/Female)	6/0
Age (years)	49.7 $\pm$ 26.8
BMI (kg/m <sup>2</sup> )	26.8 $\pm$ 3.2
Total sleep time (minute)	436.1 $\pm$ 59.6
Sleep Efficiency (%)	88.1 $\pm$ 6.2

**B. Respiration signal acquisition system**

Respiratory related signals of patients during sleep were measured using PVDF sensor. The PVDF film thickness was about 100 micrometer (part no.: 3-1004347-0, Measurement Specialties, Inc.) and it was installed between a bed mattress and the bed cover. To prevent damage to the sensor, thin silicon pad was placed on the PVDF sensor and its thickness was 1 millimeter. Consequently, total thickness of combined system was 1.1mm and it could keep the subject’s conscious awareness from sensor installation. The PVDF sensors were positioned under the patient’s back and they were composed 4x1 arrays. Fig. 1 shows the actual sensor installation on the bed and the size of the combined system. During inspiration and expiration cycle, expanded or diminished volume of the body applies different levels of pressure to the PVDF sensor and output signals of the sensor are changed. Four channel signals from the sensors were collected simultaneously with PSG data using NI-DAQ 6221 (National Instruments, Austin, Texas). The sampling rate was 250Hz.

**C. Apnea event decision algorithm**

Apnea or hypopnea events during sleep were estimated from nocturnal data from the PVDF sensors. First, respiratory-related signals were derived from PVDF data by low-pass filtering (lower than 1 Hz). After filtering, to remove baseline wondering, detrended moving average technique was adopted. Each processed signal does or does not show the respiratory state because best contact channel changes depending on sleep posture or sleep period. So, principal component analysis (PCA) method was applied to each channel signal for best channel selection. Before PCA was applied, each channel of data was normalized to have zero mean and unit variance. The correlation coefficients between PC 1 and each channel signal were calculated and the data of channel that showed the highest correlation with PC 1 was selected. Amplitude of peaks of selected respiration signal was calculated using the self-developed peak detection algorithm. Apnea or hypopnea events were estimated when following criteria are met:

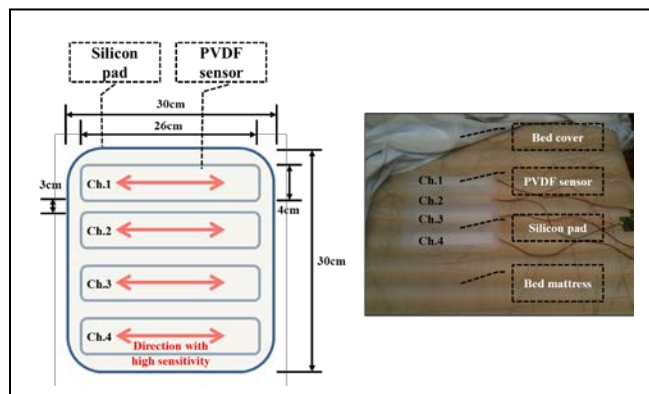


Figure 1. Sensor installation and size of combined system.

TABLE II. RESULTS OF SAS SEVERITY AND AHI ESTIMATION

Subject #	Severity (PSG / Our Method)	AHI (PSG / Our Method)
1	Severe / Severe	46.0/48.9
2	Severe / Severe	34.8/36.1
3	Moderate / Moderate	21.5/21.0
4	Severe / Severe	42.2/46.9
5	Severe / Severe	33.5/38.9
6	Moderate / Moderate	29.2/28.3
Mean ± S.D.		34.5±8.8 / 36.7±10.7

AHI (events per hour) severity; 5-15: mild, 15-30: moderate, >30: Severe  
S.D. standard deviation

- 1) Amplitude of respiration peak drops by >30% of average value of previous 7 peaks
- 2) The duration of this drop occurs for a period lasting at least 10 seconds.

These rules were determined according to the published manual for the scoring of sleep and associated events [9]. Finally, the apnea event estimation results were compared with the ones from PSG.

**III. RESULTS**

As shown in Table 2, in all patient cases, apnea severity concordance was revealed by 6 of 6 subjects (100%). Mean AHIs from our methods and PSG were 36.7±10.7 (range: 21.0-48.9) and 34.5±8.8 (range: 21.5-46.0) events per hour, respectively. The root mean square error (RMSE) between paired results was 3.2. In Fig. 2, AHI validation process between PSG and ours was evaluated by using the Pearson correlation coefficient and it was 0.982 ( $p < 0.001$ , paired sample t-test). In Fig. 3, agreement between AHI from PSG and ours was evaluated by using Bland-Altman method. In this figure, each black-dot was expressed in terms of the mean difference ± standard deviation between coupled results and all cases existed within 95% limits of agreement as dashed lines (2 x standard deviation).

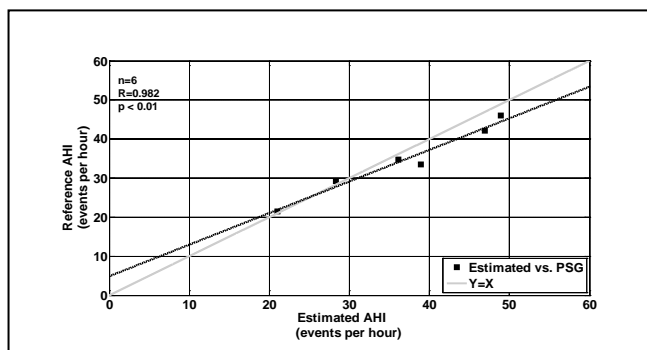


Figure 2. Correlation coefficient between PSG-AHI and estimated AHI

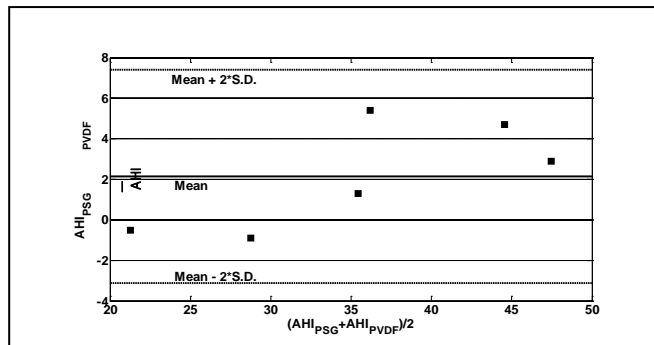


Figure 3. A Bland-Altman plot for AHI from PSG and proposed method.

#### IV. DISCUSSION

In this study, we assessed the unconstrained apnea event estimation method during sleep using the respiration signal measurement sensor. Apneic event estimation process was accomplished the following steps;

- 1) respiratory signal extraction from PVDF data
- 2) best contact channel selection
- 3) apnea or hypopnea event decision algorithm.

This sequential technique was applied to the patient's PVDF data during sleep while they can even be unaware of the recording process. AHIs from the proposed method were compared with the ones from PSG and we demonstrated a strong correlation between paired results ( $r > 0.98$ ). Furthermore, apnea severity of all participations showed perfect concordance and root mean square error between PSG and ours was only 3.2%. Consequently, our apnea event estimation method for patients with sleep apnea syndrome was proved to be comparable to PSG. Because the suggested method is simple and do not disturb subject's sleep, it can be used for long-term or ambulatory sleep apnea monitoring purpose.

AHI estimation results from the suggested study were compared with commercial systems used in ambulatory purpose. For instance, a wrist-worn device that contains an optico-pneumatic sensor, arterial oxygen saturation sensor and actigraph was used to estimate the AHI during sleep [10]. Even though the wrist-worn device includes SaO<sub>2</sub> signal that fully reflects the stop breathing, correlation coefficient between PSG and the suggested method was 0.87. Another example is NightWatch (NW) system that records eye movement, leg movement, SaO<sub>2</sub>, nasal-oral airflow, chest and abdominal wall motion, etc [11]. The correlation for AHI was 0.94 between NW and PSG and it is lower than those from our methods. However, to establish that the PVDF sensor and our method can be employed to estimate subject's apneic events successfully during sleep, more data of sleep apnea patients or normal subjects will be verified.

In our system, the PVDF sensors were composed of 4 channels under the patient's back position. During recordings, perpendicular vibration to the body which was induced respiration transfers to the sensor in horizontal direction

through the bed mattress. Since the PVDF sensor has high sensitivity in a particular direction, sensor array was aligned horizontally long and narrow. By contrast, the sensitivity of PVDF sensor is poor in thickness direction. So, when patients slept with right or left lateral posture, apnea event estimation error was relatively high compared with that from other posture (supine and prone). In PVDF channel selection procedure, channel #1 and 2 were hardly selected as best contact channel. During the PSG, most of the time, patients slept with the pillows and there is a gap between the bed mattress and upper part of the body. Because upper body of patients was not fully contacted with the PVDF sensor, channel 1 and 2 were accompanied by a relative low signal to noise ratio and this is why these channels were not selected as best contact channel.

In our study, as shown in the Fig. 3, the presented PVDF sensor-based apnea event detection method tended to overestimate the AHI for severe severity. For patients with moderate severity, RMSE between PSG-AHI and ours was only 0.7 and it was acceptable result. However, for severe severity, corresponding error was 3.9. The relatively high error from patients with severe severity occurred partly since our system estimated the respiratory signal drop as apnea events that not satisfy standard event scoring criteria. For patients with severe sleep apnea, other sleep-related breathing disorders (SRBD), such as snoring, upper airway obstruction and congestive heart failure, could occur during sleep and these SRBD can also affect the amplitude of respiratory signals [12]. Respiratory event related arousals (RERAs) during sleep may also influence respiration signal drop.

In this paper, a reliable and unconstrained method to estimate the sleep apnea events was suggested. Using the PVDF sensor, apnea event estimation performance was obtained and its result was comparable to that of PSG. We speculate that the proposed method can be used for the continuous sleep apnea ambulatory monitoring system.

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