Development of a Portable Device for Telemonitoring of Snoring and Obstructive Sleep Apnea Syndrome Symptoms

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ABSTRACT

Snoring is a very common problem and a possible sign of obstructive sleep apnea syndrome (OSAS). In clinical practice, the use of polysomnographic (PSG) recording is a standard evaluation procedure for sleep-related breathing disorder (SRBD). However, PSG is not suitable for long-term monitoring in the home environment. This paper describes the development of a portable telemonitoring device that detects and identifies snoring and OSAS symptoms in real time by analyzing the temporal features of the snoring sound. The device itself also serves as a Web server. Doctors and caregivers can access real-time and historical data via a Microsoft Internet Explorer browser or a remote application program for telemonitoring of snoring and OSAS symptoms. In our validation test with 5 regular snorers and 5 OSAS patients, this detector showed a good performance in detecting snoring and achieved an average sensitivity of 94.0% and an average positive predictive value of 94.0%. The average sensitivity of OSAS segments was 81.1%, and the average positive predictive value was 73.3%. This device is not intended to be a diagnostic device for OSAS. Instead, this portable device is to be used as a home appliance as a precautionary measure for monitoring snoring and OSAS. Once OSAS symptoms are detected, a sound recorder records a 1-minute episode, so that the patient can consult doctors for further diagnosis. This portable telemonitoring device provides a convenient approach to better understand and recognize sleep-related breathing disorders.

INTRODUCTION

Snoring is a very common problem and a possible sign of sleep-related breathing disorder (SRBD). Intermittent snoring and drops of oxyhemoglobin saturation (SaO₂) are characteristic features of obstructive sleep apnea syndrome (OSAS). In clinical practice, poly-somnographic (PSG) recording is used as the standard evaluation procedure for SRBD patients. Patients have to wear SaO₂ saturation, nasal airflow, thoracic effort, and sound sensors to do 1-night tests in a specialized laboratory. Snoring and OSAS symptoms are identified by off-line diagnosis software in a computer.

Several computer-based systems have been developed to quantitatively measure snoring using acoustic sounds. Jane et al.1 designed an automatic algorithm for detecting acoustic snoring signals based on a neural network. The input pattern of the neural network, which consists of 22 temporal and spectral features of each sound segment, distinguishes between the snoring sound and other respiratory sounds. In their validation test, more than 500 snores were randomly taken from a database of 30 patients and analyzed. The average sensitivity of the algorithm was 82% and the average positive prediction value was 90%. Sola-Soler et al.2 used a logistic regression model to classify simple snorers and OSAS patients by observing their sound intensity and other spectral parameters. The model’s parameters were adjusted to correctly classify 100% of the OSAS patients at the expense of 57.1% of regular snorers.

Because of the development of microprocessor technology, some portable systems have been designed for monitoring snoring and OSAS. Cohen3 presented algorithms utilizing a microprocessor for the quantitative and objective analysis of acoustical pulmonary signals, such as breathing and snoring sounds. Penzel et al.4,5 developed a digital recording device, called MESAM IV (MAP; Martinsried, Germany) to monitor oxygen saturation, heart rate, snoring, and body position in order to screen patients for the presence of OSAS. MESAM IV records snoring sounds by means of a laryngeal microphone. If the proportion of sounds between 50 Hz and 800 Hz exceeds 50%, it is assumed...
that patients are snoring. Intermittent snoring is defined as intervals between two detected snores that last between 5 seconds and 60 seconds. The diagnosis of OSAS was established by calculating oxygen desaturation index, heart rate variation index, and intermittent snoring index. After this development, a number of validation studies on MESAM IV were presented. In these studies, the intermittent snoring index was found to have high sensitivity (92%–96%) but low specificity (16%–27%). MESAM IV can record for periods of up to 18 hours, which makes it possible to perform examinations in a patient’s home environment and then to be diagnosed in the hospital.

Audio alarms and stimulators are widely used to stop snoring or apnea processes during sleep. Kermit et al. developed a device for early online detection of upper airway obstructions. If an obstruction is detected, an audio alarm alerts the patient to prevent the occurrence of apneic events. Çavuşoğlu et al. also proposed a similar approach to alarm a patient when the voltage of a nasal air flow sensor was below the threshold value. Miki et al. reported positive results with electrical stimulation in patients with OSAS. In their research, when apnea lasted more than 5 seconds, electrical pulses of 0.5 ms (repetition rate, 50 Hz) and 15 to 40 V were delivered through bipolar electrodes attached to the skin. The electrical pulses stopped immediately after breathing resumed or after 10 seconds. As a result, the number of times per hour that oxygen saturation dropped below 85% decreased significantly. Guilleminault et al. also presented similar procedures with stimulations that started within 5 seconds of abnormal breathing and stopped with the resumption of normal breathing.

For the needs of remote monitoring of sleep, several research activities are under way. Kristo et al. presented a telemedicine protocol for the online transfer of PSGs from a remote site to a centralized sleep laboratory, which provided a cost-saving approach for the diagnosis of OSAS. Seo et al. developed a nonintrusive health-monitoring house system to monitor patients’ electrocardiogram (ECG) results, weight, movement pattern, and snoring, in order to get information...
on patients’ health status and sleep problems. Choi et al.17 presented a ubiquitous health monitoring system in a bedroom, which monitors ECG, body movements, and snoring with nonconscious sensors.

A centralized framework is used in most home telehealth systems, in which a centralized database is used for data storage and analysis. Figure 1 shows the structure of the Portable Telehomecare Monitoring System (PTMS) developed by the authors.18 The PTMS is a decentralized home telehealth system. Instead of using a centralized database that gathers data from many households, a single household is the fundamental unit for sensing, data transmission, storage, and analysis in the PTMS. The monitoring data are stored in the Distributed Data Server (DDS) inside a household.

As shown in Figure 1, sensing data from sensors embedded in the home environment are transmitted to the DDS. Sensing signals are then processed and stored in the DDS. Authorized remote users can request data from the DDS using an Internet Web browser (through an application server) or a Visual Basic (VB) program (direct access to the DDS). Event-driven messages (mobile phone text messages or e-mails) can be sent to specified caregivers when an urgent situation is detected.

There are several advantages of the PTMS structure over the traditional centralized database structure:

1. The scale of the PTMS is much smaller, which makes it economically viable and acceptable to the end-users. A single household can be a running unit of the PTMS. This distributed structure can be adapted if a centralized database is needed.
2. Instead of sending the health monitoring data to a centralized database in a home healthcare provider, health monitoring data are stored within the household. Only authorized caregivers can access the data. Privacy is better protected.
3. The route from the sensor to server is much shorter. Data transmission is easier and more reliable. When the Internet communication fails, the local system can still function normally and keep collecting data. Thus, data integrity is better preserved.

This paper describes the development of a Snoring and OSAS symptom Detector (SOD), which is designed for long-term monitoring at home based on the PTMS structure. The SOD is not intended to be a diagnostic device for OSAS. Instead, this portable device is to be used as a home appliance as a precautionary measure for monitoring snoring and OSAS. The SOD on-line monitors snoring and intermittent snoring pattern, which is the characteristic symptom of OSAS, and stores the monitoring data. Users and caregivers can access the SOD for historical monitoring data via the Internet.

Fig. 2. Structure of the snoring and obstructive sleep apnea syndrome symptom detector. DDS, Distributed Data Server; MMC, multi-media card; IE, Microsoft Internet Explorer; GSM, Global System for Mobile Communications.
MATERIALS AND METHODS

Figure 2 shows the structure of the SOD developed in this research. Similar to the PTMS structure in Figure 1, the core component of the SOD is a DDS that analyses sound signals captured by a microphone and selects snoring and OSAS symptoms using the snore and OSAS detecting algorithms. The DDS consists of a PIC server mounted on a peripheral application board. The PIC server integrates a PIC microcontroller (PIC18F6722, Microchip), EEPROM (24LC1025, Microchip), and a networking IC (RTL8019AS, Realtek). It provides networking capability and can be used as a Web server.

The counts of snoring and intermittent snoring pattern per minute, as well as the duration of intermittent snoring pattern, are recorded in the Multi-Media-Card (MMC) of the DDS. Authorized remote users can request data from the DDS using an Internet Web browser (through an application server) or a VB program (direct access to the DDS).

This portable telemonitoring device provides a convenient approach to better understand and recognize sleep-related breathing disorders. Patients whose snoring patterns are classified as possible OSAS symptoms by the SOD should consult physicians for further diagnosis. For this purpose, a sound recorder is activated to record a 1-minute episode for further diagnosis, once an OSAS symptom is detected. In the meantime, a low-frequency electrical stimulation can be given to the patient in order to stop the development of an apneic process. If an urgent situation is detected, an emergency message (mobile phone short messages or e-mails) can be sent to specified caregivers.

The rest of this paper is organized as follows. Section 2 and Section 3 presents the algorithm design and network framework of the SOD. Section 4 discusses the validation results of the SOD. In conclusion, Section 5 describes the applications and benefit of the SOD.

DESIGN OF THE SNORING AND OSAS SYMPTOM DETECTING ALGORITHMS

As shown in Figure 2, an omnidirectional electret condenser–type microphone is used in the SOD to record the snoring sounds. A fifth-order, low-pass filter removed high-frequency sounds. The frequency response of the microphone is within 50–30,000 Hz, and the cutoff frequency of the low-pass filter is 200 Hz. The analog signals are digitized at a sampling frequency of 2 kHz with a 10-bit A/D converter in a PIC server. The signals are processed by a series of smoothing procedures and analyzed with the snoring and OSAS detecting algorithms. The following sections describe this procedure in detail.

SMOOTHING AND SIMPLIFYING PROCEDURES

Figure 3a shows the input snoring sound signals. A series of smoothing and simplifying procedures further process these signals:

1. The differences between the input voltages and the baseline voltage are calculated (Fig. 3a).
2. The absolute values of the differences are taken to get all positive values (Fig. 3b).
3. A moving average filter with a window size of 20 smoothes the profile of the input voltage values.

Fig. 3. (A) Input voltages and the baseline voltage. (B) Absolute value of the differences. (C) Smoothed and simplified values of the input voltage.
Fig. 4. (A) Slope values of snoring signals. (B) Slope code of snoring sounds (threshold limit value = 0.003). (C) Snoring episodes located with the slope mapping method.
4. To save computational resource in the following snoring-detecting algorithm, the signals are further simplified to 10 data points per second (Fig. 3c).

SNORING DETECTING ALGORITHM

After the smoothing and simplifying procedure, the snoring detecting algorithm analyzes the data for detecting and locating snores by the following steps:

1. Calculate the slope values of snoring signals in Figure 3c, as shown in Figure 4a.
2. Symbolize a slope value with a snoring code “1” if it is above the threshold limit and a “0” if the slope value is under the threshold limit. Figure 4b shows this “slope mapping” of the first two snores in Figure 4a, using a threshold limit 0.003.
3. Identify snores if the slope mapping result matches the length definition of a snore (Fig. 4c).

To determine the length definition of a snore, 5,024 snoring samples from 5 patients who were diagnosed as having sleep-related breathing disorders were collected and analyzed. Using the same threshold limit 0.003, it was found that the duration (the length of a series of snoring code “1”) of 99% of the snores ranged from 0.6 seconds to 1.8 seconds. This duration is used in the snoring detecting algorithm in SOD.

OSAS SYMPTOM DETECTING ALGORITHM

Figure 5 shows a typical waveform of an OSAS symptom, where the patient stopped breathing after a series of snores and started breathing again after 34 seconds. The Apnea-Hypopnea Index (AHI) is an index of severity that combines apneas and hypopneas. AHI is calculated by dividing the number of apneas and hypopneas by the number of hours of sleep. In MESAM IV described in Section 1, intermittent snoring intervals lasting between 10 and 60 seconds are assumed to be an intermittent snore. An intermittent snoring interval longer than 60 seconds may be a sign that the patient stops snoring and breathes normally, and will not be assumed as an OSAS symptom. The Intermittent Snoring Index (ISI), which was defined as the number of pauses in snoring lasting 10 to 60 seconds per hour, was one of the indices used in MESAM IV for automatic scoring of OSAS.

Both AHI and ISI are calculated off-line. To identify the OSAS symptom in real time, the Intermittent Snoring Ratio (ISR) is defined for describing the intermittent snoring pattern for each minute. The SOD tallies intermittent snore counts (intermittent snoring intervals...
lasting between 10 and 60 seconds) and total snore counts (normal snore counts plus intermittent snore counts) within the current minute. The location of normal snore and intermittent snore is decided by the endpoint of the snoring episode. At the end of the minute, ISR is calculated by

$$\text{ISR} = \frac{\text{intermittent snore counts}}{\text{total snore counts}}$$  \hspace{1cm} (1)

To consider the tendency of ISRs for the past 5 minutes (including the current minute), the Weighted-ISR (W-ISR) is calculated by

$$\text{Weighted } \text{ISR}_i = \frac{5}{12} \cdot \text{ISR}_i + \frac{4}{12} \cdot \text{ISR}_{i-1} + \frac{2}{12} \cdot \text{ISR}_{i-2} + \frac{2}{12} \cdot \text{ISR}_{i-3} + \frac{1}{12} \cdot \text{ISR}_{i-4}$$  \hspace{1cm} (2)

High W-ISR represents a frequent intermittent snoring pattern in the past 5 minutes. Therefore, the intermittent snore in the current minute is more likely to be an OSAS symptom, instead of a sign that the patient stops snoring and breathes normally. The maximum W-ISR is 1, which means that all snores in the past 5 minutes are intermittent snores. In this research, the SOD calculates W-ISR values and classifies the intermittent snore in the past minute as an OSAS symptom if the W-ISR value is higher than 0.25.

Figures 6 and 7 show 6-hour records of the W-ISRs of a regular snorer and a patient who was diagnosed to have OSAS. W-ISRs are high for the OSAS patient and relatively lower for the regular snorer. Figure 8 shows a 1-hour record of W-ISRs (4:00–5:00 AM). The periods in which OSAS symptoms occur identified by the SOD using W-ISRs match well with those diagnosed by PSG using SaO₂ saturation, nasal airflow, and thoracic effort sensors.
USER INTERFACE AND NETWORK FRAMEWORK

Figure 9 shows a prototype of the SOD developed in this research. The SOD can be easily installed by connecting the power line and the Internet cable. During monitoring, the numbers of snore counts per minute, intermittent snore counts per minute, as well as W-ISR are shown on the LCD display and stored in the multi-media card (MMC). Two external modules, a sound recorder, and a transcutaneous electrical nerve stimulator (TENS SW32012, SHINMED), can also be connected to the SOD (Fig. 10). Once OSAS symptoms are detected, low-frequency transcutaneous electrical nerve stimulation can be given to the patient in order to stop the development of an apneic process. The sound recorder is also activated to record a 1-minute episode for further diagnosis.

Figure 11 shows the network framework for the SOD. Physicians and caregivers can access real-time and historical data via a remote VB program. Figure 12a shows the VB interface window designed for the SOD. After typing an IP address and clicking the “real-time” button, real-time information of snore count, intermittent snore count,
and W-ISR are displayed on the left side of the interface window. An OSAS alarm will be flagged when W-ISR is higher than 0.25. Physicians and caregivers can monitor 3 patients on the same window. Selecting one of the IP addresses on the left side, the user can also download historical data from the SOD at this IP address (select a date and time interval on the right side of the interface window and click the “download” button). Diagnosis reports for total snore count, total intermittent snore count, and total OSAS segments (in minutes) within the selected time interval can be tallied automatically. Charts of snore counts per minute versus time, intermittent snore counts per minute versus time, and OSAS segments versus time can also be drawn for further analysis (Fig. 12b–d).

Fig. 10. External modules of snoring and obstructive sleep apnea syndrome symptom detector. TENs, transcutaneous electrical nerve stimulator; SOD, snoring and OSAS symptom detector.

Fig. 11. A framework for the snoring and obstructive sleep apnea syndrome symptom detector (SOD). SMTP, simple mail transfer protocol; GSM, Global System for Mobile Communications.
RESULTS

Two validation tests were designed to evaluate the performance of the snoring and OSAS symptom detector. The first test is for snore detecting validation, in which the SOD was used to detect snores of 5 regular snorers and 5 OSAS patients in whole-night’s sleep. All automatically detected snores by the SOD were checked by manual annotations.

One problem with manual annotation was that the definition of snoring varies between observers. Hoffstein et al. pointed out that

Fig. 12. (A) Visual Basic interface window for the snoring and obstructive sleep apnea syndrome symptom detector. MMC, multi-media card; W-ISR, weighted intermittent snoring ratio. (B) Snore counts per minute versus time. (Continued)
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Fig. 12. (C) Intermittent snore count per minute versus time. (D) Obstructive sleep apnea syndrome (OSAS) segments versus time.

Fig. 13. Test environment and test equipment. PSG, polysomnogram; SOD, snoring and obstructive sleep apnea syndrome detector.
the difficulty in measuring and quantifying snoring using objective criteria is that snoring is the first and foremost of a subjective perception by a listener. They studied 25 cases (all had full nocturnal polysomnography including the measurements of snoring) to compare the objective snore count from the polysomnogram and the subjective snoring count by 2 listeners during a 20-minute segment. In 7 of 25 patients, the difference in subjective snore counts perceived by both listeners was greater than 25%.

To reduce the uncertainty of subjective judgments, a sound level meter (TES 1350A, TES Electrical Electronic Corp.) was used to record the sound level of each snore. A snoring segment greater than 60 dB was classified as a snore and segments less than 60 dB were classified by the observers’ own judgments. A camcorder was used to record the colored light-emitting diode lights of the SOD, which flash when snoring episodes were detected, and the display panels of both the sound level meter and the clock. Figure 13 shows the test environment and test equipment.

A trained observer viewed the entire night’s sleep videos and checked each snore identified by the SOD by manual annotations. The comparison was coded as one of the following: True Positive (TP), False Negative (FN), or False Positive (FP). Table 1 shows the validation results of snoring detection. The SOD showed a good performance in detecting snore and achieved an average sensitivity of 94.0% (range 83.4%–99.8%) and an average positive predictive value (PPV) of 94.0% (range 83.3%–99.9%).

In the second test, OSAS symptoms judged by the SOD with W-ISR were compared with the diagnosis reports by a PSG. A 1-minute segment was coded TP if the SOD and PSG both detected OSAS.
symptoms within the minute. Similarly, a segment was coded FP or FN if only the SOD or only the PSG detected OSAS symptoms within the minute. Table 2 shows the validation results of locating OSAS segment of the 5 OSAS patients. The average sensitivity of locating OSAS segments was 81.1% (range 62.2%–96.3%) and the average PPV was 73.3% (range 41.6%–93.6%) in the OSAS patient group.

In the meantime, 360 minutes of recorded data were collected from 5 regular snorers for evaluation of the success rate of recognizing normal segments (non-OSAS segments). Segments with W-ISR below 0.25 were classified as normal segments. The average sensitivity of recognizing normal segments was 81.1% (Table 3), that is, 18.9% of the non-OSAS segments were falsely identified as OSAS segments.

CONCLUSIONS

OSAS is characterized by apnea during sleep usually after snoring. Recent research has shown that there is a high prevalence of OSAS in snorers and a high incidence of cardiovascular disease in OSAS patients. A portable device for tele-monitoring of snoring and OSAS symptoms has been developed in this research to evaluate snoring with quantitative measurement and detect OSAS symptoms with the W-ISR in real time. In our validation tests, the sensitivity and positive predictive value of detecting snoring are no different between regular snorers and OSAS patients. Furthermore, the W-ISR is a useful index to represent the character of intermittent snoring and achieved good sensitivities of locating OSAS segments and normal segments.

The SOD is a nonobtrusive user-centered device that allows users to easily set up a personal monitoring system at home and gain a better understanding of their sleep problems. As mentioned in Section 1, the SOD is one of the many applications of the Portable Telehomecare Monitoring System (PTMS). What sets the PTMS apart from most other systems is the focus on a highly decentralized monitoring model and the portable nature of the system. We believe that this is the approach that is needed to make such systems economically viable and acceptable to the end-users.

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REFERENCES


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