Monitoring Sound To Quantify Snoring and Sleep Apnea Severity Using a Smartphone: Proof of Concept

Hiroshi Nakano, Ph.D.¹; Kenji Hirayama, Ph.D.¹; Yumiko Sadamitsu, R.N.¹; Ayaka Toshimitsu, M.T.¹; Hisayuki Fujita, M.T.¹; Shizue Shin, M.T.¹; Takeshi Tanigawa, Ph.D.²

¹*Sleep Disorders Center, Fukuoka National Hospital, Fukuoka City, Japan;* ²*Department of Public Health, Ehime University Graduate School of Medicine, Shitsukawa, Toon, Ehime, Japan*

Study Objectives: Habitual snoring is a prevalent condition that is not only a marker of obstructive sleep apnea (OSA) but can also lead to vascular risk. However, it is not easy to check snoring status at home. We attempted to develop a snoring sound monitor consisting of a smartphone alone, which is aimed to quantify snoring and OSA severity.

Methods: The subjects included 50 patients who underwent diagnostic polysomnography (PSG), of which the data of 10 patients were used for developing the program and that of 40 patients were used for validating the program. A smartphone was attached to the anterior chest wall over the sternum. It acquired ambient sound from the built-in microphone and analyzed it using a fast Fourier transform on a real-time basis.

Results: Snoring time measured by the smartphone highly correlated with snoring time measured by PSG ($r = 0.93$). The top 1 percentile value of sound pressure level (L1) determined by the smartphone correlated with the ambient sound L1 during

sleep determined by PSG ($r = 0.92$). Moreover, the respiratory disturbance index estimated by the smartphone (smart-RDI) highly correlated with the apnea-hypopnea index (AHI) obtained by PSG ($r = 0.94$). The diagnostic sensitivity and specificity of the smart-RDI for diagnosing OSA (AHI ≥ 15) were 0.70 and 0.94, respectively.

Conclusions: A smartphone can be used for effectively monitoring snoring and OSA in a controlled laboratory setting. Use of this technology in a noisy home environment remains unproven, and further investigation is needed.

Keywords: Snoring, home monitoring, obstructive sleep apnea, smartphone

Commentary: A commentary on this article appears in this issue on page 79.

Citation: Nakano H; Hirayama K; Sadamitsu Y; Toshimitsu A; Fujita H; Shin S; Tanigawa T. Monitoring sound to quantify snoring and sleep apnea severity using a smartphone: proof of concept. *J Clin Sleep Med* 2014;10(1):73-78.

Habitual snoring is an extremely prevalent condition affecting 22% to 44% of middle-aged males and 13% to 28% of middle-aged females.¹⁻³ It is a key symptom suggesting the possibility of obstructive sleep apnea (OSA). Moreover, it has been suggested that snoring can be a vascular risk.^{4,5} Primary snoring is readily affected by body position⁶; it may decrease or increase with loss or gain in body weight.⁷ Decrease in snoring reduces the risk of sleep disordered breathing. Therefore, self-monitoring of snoring is considered to be a useful tool for maintaining good health among the general population. However, no device is currently available for home monitoring of snoring. Recently, smartphones with various sensors and signal processing capabilities have been used as tools for home healthcare (for example, as a pedometer, an exercise pulse rate monitor, and an advisory service for dietary control). Moreover, a growing body of biomedical engineering research demonstrated that snoring characteristics carry very useful information about OSA severity.⁸⁻¹⁵ We attempted to develop a snoring sound monitor consisting of a smartphone alone. The system was designed for quantifying snoring as well as OSA severity.

METHODS

Subjects

The subjects included 50 patients who underwent diagnostic PSG for suspected sleep apnea. The study was approved by our

BRIEF SUMMARY

Current Knowledge/Study Rationale: Snoring is suggested to be a vascular risk regardless of coexistence of obstructive sleep apnea (OSA). However, no validated device is currently available for home monitoring of snoring.

Study Impact: This study demonstrated that a smartphone can be used for effectively monitoring snoring and OSA in a controlled laboratory setting. Further studies under practical conditions are needed.

institutional review board, and all patients gave their written informed consent.

Smartphone

An ordinary smartphone in Japan (SH-12C, Sharp Corp., Osaka, Japan) was used as the snoring sound monitor. It was attached to the anterior chest wall over the sternum using adhesive tape. The opening of the built-in microphone was directed toward the neck.

Acquisition of Sounds

The smartphone operated on the Android system (version 2.33). A custom-made program on the smartphone acquired ambient sounds from the built-in microphone and analyzed it on a real-time basis. The procedure of signal processing was as follows: the system acquired sound data for approximately 0.1 s (11025-Hz sampling frequency, 1024 points, Hanning

Figure 1—Representative trace showing relationship between polysomnograph signals and smartphone-acquired sounds

(A) Polysomnography signals. One obstructive apnea (OA) and 3 obstructive hypopnea (OH) events are detected during the 5 minutes data. Tracheal sound spectrogram shows snoring (indicated by red color) predominantly during hypopnea events. (B) Smartphone-acquired sounds. The parameters for detection of snoring (total power, peak power spectral density) and respiratory events (filtered total power time series) are shown. Arrows indicate the sound power dips detected at a threshold of 3 dB (see text).

window), calculated power spectra using a fast Fourier transform, and stored these on the memory of the smartphone; this process was repeated every 0.2 s. Although this procedure discards half the data, it seems sufficient for the acquisition of snoring sound. The sound acquisition procedure was identical to that developed for tracheal sound monitoring to detect OSA.¹⁵

Analysis of the Sounds

Sound Intensity

The program was calibrated once using a reference sound pressure level (94 dB [0 dB = 20 μ Pa], 1 kHz) during its development. A sound calibrator (SC-2120A; Ono Sokki, Yokohama, Japan) was connected to the smartphone at the opening of the built-in microphone using a custom-made attachment to ensure a sealed connection. The program calculated the top 1 percentile sound pressure level (L1) and the equivalent sound pressure level (Leq) in dB from the all-night data as variables of snoring sound intensity.¹⁶

Detection of Snoring Sound

Recorded spectra of the 10 development group subjects were displayed as spectrograms (**Figure 1**), from which the segments with features characteristic of snoring were selected to determine the spectral parameters for snoring detection. These parameters were adjusted to maximize the association between snoring time measured with the smart phone and that taken from PSG tracheal sounds.

Detection of Respiratory Events

Sound power (in dB, 50-2000 Hz) time series data were generated and low-pass filtered (cutoff frequency 0.05 Hz), from which we detected sound power dips fulfilling the following criteria (**Figure 1**): the sound power dip was defined as a dip in more than a given threshold value in the time series, lasting ≤ 90 s, with the descending and ascending portions steeper than the threshold value per 18 s. The dip was assumed to correspond to a respiratory event.¹⁵ We defined the smart-RDI as the number of sound power dips per hour of examination. The optimal threshold for the dip was determined from the 10 development group patients' data, based on the value that maximizes the association between the smart-RDI and PSG-AHI.

Polysomnography

The sensors for PSG along with the smartphone were fixed by technicians, but the sensors were not monitored after the start of the recording. PSG was recorded using a polygraph system (EEG7414; Nihon Kohden, Tokyo, Japan). Nasal airflow was monitored with a nasal prong pressure transducer (PTAF; Pro-Tec, Mukilteo, WA, USA). Thoracic and abdominal respiratory movements were monitored with respiratory inductive plethysmography (Q-RIP; Braebon Medical Corp., Kanata, Ontario, Canada). Oxyhemoglobin saturation was monitored using a pulse oximeter (OLV-3100; Nihon Kohden, Tokyo, Japan) at the fastest response mode.

Tracheal sound was recorded from an air-coupled microphone (ECM-PC60, SONY, Tokyo, Japan) attached on the neck

Figure 2—The relationship between the equivalent sound pressure level (Leq) determined by the smartphone and that of tracheal sounds and ambient sounds during sleep determined by polysomnography

over the trachea. The recording system of tracheal sound was calibrated using a reference sound pressure level (94 dB) in the same way as the smartphone system. Tracheal sounds were digitized by the sound system incorporated in a personal computer (PC) at a sampling frequency of 11025 Hz. To evaluate snoring sound intensity, ambient sound pressure was also recorded using a sound level meter (LA1200; Ono Sokki, Yokohama, Japan). The microphone of the sound level meter was suspended 1.2 m above the surface of the patient's bed. The ambient sound intensity was measured as an A-weighted sound pressure level with a time constant of 125 ms. The measured sound pressure level was inputted to the polygraph system as an analogue signal and digitized simultaneously with the other PSG signals.

The recording by PSG and the smartphone were started simultaneously. Sleep stages were scored manually according to standard criteria. Apnea was defined as cessation of airflow lasting ≥ 10 s. Hypopnea was defined as an episode of airflow amplitude reduction ($> 50\%$) lasting ≥ 10 s and associated with $\geq 3\%$ oxygen desaturation or an arousal.¹⁷ The apnea-hypopnea index (AHI) was calculated as the number of apnea and hypopnea events per hour of sleep. Snoring was detected from the tracheal sound data automatically using the criteria in which a peak value of power spectral density ≥ 70 dB/Hz, which means a power spectrum of about 80 dB at the frequency resolution of 10.8 Hz (11025-Hz sampling and 1024 points window), within the frequency bandwidth of 100-300 Hz was defined as snoring.⁶ Thereafter, we examined the whole overnight sound spectrogram and excluded body movement sounds and voice sounds from the automatically detected segments. As a variable of snoring sound intensity, we calculated the L1 and Leq during sleep from tracheal sound spectra data recorded every 0.2 s during PSG.¹⁸ In addition, the L1 and Leq during sleep were calculated from the ambient sound level data, because variables from the tracheal sounds were found to suffer a ceiling effect in patients with loud snoring.

Analysis

The subjects were divided into the development group ($n = 10$) and the validation group ($n = 40$). The spectral parameters for detecting snoring and the threshold for detecting sound power dips were determined using data from the development group subjects. Comparisons between the snoring time using the smartphone and that using PSG tracheal sounds and between the smart-RDI and AHI were performed using data from the validation group subjects. The L1 and Leq values determined by the smartphone were compared with those of tracheal sounds and ambient sounds determined by PSG in all subjects. All variables from PSG were calculated for total sleep time (TST) with denominator of TST, while the compared variables from smartphone were calculated for entire examination time with denominator of examination time. The smartphone data were analyzed using a custom-made PC program, which can be implemented on a smartphone, and no manual editing was made.

RESULTS

Characterization of Subjects

Of the 50 subjects, 42 were males and 8 were females. The mean age of the subjects was 47.9 years (SD 13.7 years), and the mean body mass index was 26.4 (SD 6.1). The mean AHI was 27.3 (SD 26.1). Eleven patients were not apneic ($\text{AHI} < 5$), 10 patients had mild OSA ($\text{AHI} 5\text{--}14.9$), 12 patients had moderate OSA ($\text{AHI} 15\text{--}29.9$), and 17 patients had severe OSA ($\text{AHI} \geq 30$).

Snoring Sound

The L1 value using the smartphone correlated with the tracheal sound L1 ($r = 0.75$) and ambient sound L1 ($r = 0.92$) during sleep using PSG (**Figure 2**, $n = 50$). The Leq value

Figure 3—The relationship between the top 1 percentile sound pressure level (L1) determined by the smartphone and that of tracheal sounds and ambient sounds during sleep determined by polysomnography

Figure 4—The relationship between the snoring time determined by the smartphone and that determined by polysomnography (tracheal sounds)

Figure 5—The relationship between the respiratory disturbance index determined by the smartphone (smart-RDI) and the apnea-hypopnea index (AHI) determined by polysomnography

using the smartphone correlated with the tracheal sound Leq ($r = 0.72$) and ambient sound Leq ($r = 0.82$) during sleep using PSG (**Figure 3**, $n = 50$).

The parameters for detecting snoring were determined by the data of the development group subjects. Consequently, the following 3 parameters were determined: power spectral peak density > 35 dB/Hz, which means a power spectrum of about 45 dB at the frequency resolution of 10.8 Hz (11025-Hz sampling and 1024 points window), and between 50 and 300 Hz; total power exceeding the lowest level during the

preceding 5 s by > 6 dB; and continuing for 0.4–3.0 s. If a data segment fulfilled all 3 conditions, it qualified as snoring.

Snoring time (% examination time) measured using the smartphone and based on the above criteria highly correlated with the snoring time (% TST) determined using PSG in the validation group (**Figure 4**; $r = 0.93$, $n = 40$).

Apnea and Hypopnea

The data from the development group subjects were divided into 80 1-h segments. The number of sound power dips detected by the smartphone at various thresholds and that of

apnea-hypopnea events detected by PSG were compared in each segment. The correlation between both numbers was highest at a threshold of 3 dB, which was adopted as the threshold for the validation of the smart-RDI.

Comparison of the smart-RDI and AHI in all 40 subjects of the validation group revealed a high correlation (**Figure 5**; $r = 0.94$). Bland-Altman analysis showed that the mean difference between the smart-RDI and AHI was -6.0 and the limit of agreement was -25.0 to 13.1 (**Figure 6**). The diagnostic sensitivity and specificity of the smart-RDI in the validation group are shown as receiver operating characteristic curves (**Figure 7**). The sensitivity was moderate and the specificity was relatively high.

DISCUSSION

We attempted to use a smartphone for monitoring snoring and OSA. The smartphone program to detect snoring and OSA events was developed using data from 10 patients and validated using data from the other 40 patients and proved to be considerably effective in detecting snoring and OSA events.

Many screening tools based on questionnaires use snoring as a key symptom of OSA.^{19,20} However, it may be difficult for a single adult to answer these questionnaires accurately because most snorers are unaware of their snoring.²¹ Objectively measured snoring intensity is known to correlate with pleural pressure swing amplitude²² and OSA severity.⁸ A study in rabbits demonstrated that exposure to vibrations induced carotid artery endothelial dysfunction in a vibration energy dose-dependent manner, suggesting the importance of snoring intensity.⁵ We reported that ambient sound L1 during sleep is related to sleepiness and daytime blood pressure independent of obesity and OSA.^{23,24} We therefore suggest that a simple method using a smartphone to measure snoring is useful not

only for screening OSA but also for evaluating snoring as a detrimental symptom.

The present study has limitations that have to be addressed. First, the subjects were patients with symptoms suggestive of OSA. It is therefore necessary to test the method in the general population. Second, the recording was performed in a single room for polysomnography. In the presence of a bed partner, measurement of snoring and OSA may be affected by various sounds, including the bed partner's snoring. Third, the performance of the monitor should be dependent on the characteristics of the smartphone. Therefore, the parameters to detect snoring and OSA events need to be tuned appropriately to each

Figure 6—Bland-Altman plots showing variance between the respiratory disturbance index determined by the smartphone (smart-RDI) and the apnea-hypopnea index (AHI) determined by polysomnography

Black horizontal lines indicate 95% limits of agreement.

Figure 7—Receiver operating characteristic curve showing the relationship between diagnostic sensitivity and specificity of the respiratory disturbance index by smartphone (smart-RDI) in the validation group when the following cutoff values are used: (A) apnea-hypopnea index (AHI) ≥ 15 , (B) AHI ≥ 30

specific smartphone. Finally, the results suggest that the correlation between the smart-RDI and AHI was not as good for subjects with an AHI less than 30. Therefore, the smartphone program may have insufficient diagnostic accuracy for use as a screening tool to rule out milder forms of OSA.

The present study presents the concept that a smartphone can be used for monitoring snoring and OSA. This method cannot be used as a substitute for the type 4 OSA monitor because the reliability of the method depends on the environment and the device. However, it may be a very useful tool for individuals to check the status of their snoring and OSA daily when attempting various behavioral modifications, e.g., changes in sleeping posture or decrease in body weight. Further studies under practical conditions are warranted.

REFERENCES

1. Young T, Palta M, Dempsey J, Skatrud J, Weber S, Badr S. The occurrence of sleep-disordered breathing among middle-aged adults. *N Engl J Med* 1993;328:1230-5.
2. Kim J, In K, Kim J, et al. Prevalence of sleep-disordered breathing in middle-aged Korean men and women. *Am J Respir Crit Care Med* 2004;170:1108-13.
3. Cano-Pumarega I, Dura'n-Cantolla J, Aizpuru F, et al. Obstructive sleep apnea and systemic hypertension. *Am J Respir Crit Care Med* 2011;184:1299-304.
4. Lee SA, Amis TC, Byth K, et al. Heavy snoring as a cause of carotid artery atherosclerosis. *Sleep* 2008;31:1207-13.
5. Cho JG, Witting PK, Verma M, et al. Tissue vibration induces carotid artery endothelial dysfunction: a mechanism linking snoring and carotid atherosclerosis? *Sleep* 2011;34:751-7.
6. Nakano H, Ikeda T, Hayashi M, Ohshima E, Onizuka A. Effects of body position on snoring in apneic and nonapneic snorers. *Sleep* 2003;26:169-72.
7. Hoffstein V. Snoring. *Chest* 1996;109:201-22.
8. Maimon N, Hanly PJ. Does snoring intensity correlate with the severity of obstructive sleep apnea? *J Clin Sleep Med* 2010;6:475-8.
9. Fiz JA, Jané R, Solà-Soler J, Abad J, García MA, Morera J. Continuous analysis and monitoring of snores and their relationship to the apnea-hypopnea index. *Laryngoscope* 2010;120:854-62.
10. Karci E, Dogrusoz YS, Ciloglu T. Detection of post apnea sounds and apnea periods from sleep sounds. *Conf Proc IEEE Eng Med Biol Soc* 2011;2011:6075-8.
11. Solà-Soler J, Fiz JA, Morera J, Jané R. Bayes classification of snoring subjects with and without sleep apnea hypopnea syndrome, using a Kernel method. *Conf Proc IEEE Eng Med Biol Soc* 2011;2011:6071-4.
12. Lee LA, Yu JF, Lo YL, et al. Energy types of snoring sounds in patients with obstructive sleep apnea syndrome: a preliminary observation. *PLoS One* 2012;7:e53481.

13. Mesquita J, Solà-Soler J, Fiz JA, Morera J, Jané R. All night analysis of time interval between snores in subjects with sleep apnea hypopnea syndrome. *Med Biol Eng Comput* 2012; 50:373-81.
14. Ben-Israel N, Tarasiuk A, Zigel Y. Obstructive apnea hypopnea index estimation by analysis of nocturnal snoring signals in adults. *Sleep* 2012;35:1299-305.
15. Nakano H, Hayashi M, Ohshima E, Nishikata N, Shinohara T. Validation of a new system of tracheal sound analysis for the diagnosis of sleep apnea-hypopnea syndrome. *Sleep* 2004;27:951-7.
16. Wilson K, Stoohs RA, Mulrooney TF, et al. The snoring spectrum: acoustic assessment of snoring sound intensity in 1,139 individuals undergoing polysomnography. *Chest* 1999;115:762-70.
17. Iber C, Ancoli-Israel S, Chesson A, Quan SF. The AASM Manual for the Scoring of Sleep and Associated Events: Rules, Terminology and Technical Specifications. Westchester, IL: American Academy of Sleep Medicine, 2007.
18. Nakano H, Hirayama K, Sadamitsu Y, Shin S, Iwanaga T. Mean tracheal sound energy during sleep is related to daytime blood pressure. *Sleep* 2013;36:1361-7.
19. Netzer NC, Stoohs RA, Netzer CM, Clark K, Strohl KP. Using the Berlin Questionnaire to identify patients at risk for the sleep apnea syndrome. *Ann Intern Med* 1999;131:485-91.
20. Takegami M, Hayashino Y, Chin K, et al. Simple four-variable screening tool for identification of patients with sleep-disordered breathing. *Sleep* 2009;32:939-48.
21. Hoffstein V, Mateika S, Anderson D. Snoring: is it in the ear of the beholder? *Sleep* 1994;17:522-6.
22. Miyazaki S, Itasaka Y, Ishikawa K, Togawa K. Acoustic analysis of snoring and the site of airway obstruction in sleep related respiratory disorders. *Acta Otolaryngol Suppl* 1998;537:47-51.
23. Nakano H, Furukawa T, Nishima S. Relationship between snoring sound intensity and sleepiness in patients with obstructive sleep apnea. *J Clin Sleep Med* 2008;4:551-6.
24. Furukawa T, Nakano H, Hirayama K, et al. Relationship between snoring sound intensity and daytime blood pressure. *Sleep Biol Rhythms* 2010;8:245-53.

SUBMISSION & CORRESPONDENCE INFORMATION

Submitted for publication June, 2013

Submitted in final revised form August, 2013

Accepted for publication August, 2013

Address correspondence to: Hiroshi Nakano, Sleep Disorders Center, Fukuoka National Hospital, 4-39-1, Yakatabaru, Minami-ku, Fukuoka City, Japan; Tel: +81-92-565-5534; Fax: +81-92-566-9444

DISCLOSURE STATEMENT

This was not an industry supported study. This study was supported by a grant from a Health and Labor Sciences Research Grant (22110201), Ministry of Health, Welfare and Labor. The authors have indicated no financial conflicts of interest.