Introduction

Sleep disordered breathing (SDB), a chronic disease in which breathing partially or completely ceases during sleep, has a worldwide prevalence of 4–7%. Obstructive sleep apnea (OSA), the most common form of SDB, is characterized by symptomatic and repetitive partial or complete collapse of the airway.\(^1,2\) This instability arises from the structural vulnerability of the upper airway and loss of muscle tone during sleep.\(^3\) Recently, OSA has been recognized as an important public health problem, being associated with an increased risk of cancer, athero-
sclerosis, cardiovascular disease, stroke, hypertension, and mental health problems such as dementia and cognitive abnormalities. In OSA patients, sleep position affects the frequency of obstructive respiratory events. In the supine position, OSA is exacerbated in terms of apnea frequency, duration, and desaturation, as well as the duration of arousals. Positional dependency is defined as a supine apnea-hypopnea index (AHI) at least twice that of a nonsupine AHI, and is evident in 50–70% of OSA patients.

Snoring, the most common symptom of OSA, is caused by turbulent airflow through narrowed upper airways. Nakano, et al. showed that snoring intensity and duration decreased when OSA patients changed their sleep posture from supine to lateral. However, this was observed only in patients with AHIs less than 15. Confirmation of snoring changes in positional OSA patients is required. In this study, only patients with positional OSA were included. We aimed to identify correlations of changes in snoring sounds when patients changed their sleep position (from supine to lateral) with the AHI and other parameters. We also measured the formant frequency of snoring sounds by sleep position.

**Subjects and Methods**

Patient medical histories were obtained and physical examinations were performed prior to overnight polysomnography (PSG). During PSG, snoring sounds were recorded for subsequent analysis.

Patients complaining of snoring and OSA, who underwent physical examination and overnight PSG in our sleep clinic from July 2017 to May 2018, were enrolled in this study. We also calculated the body mass index (BMI) and examined the nasal and oral cavities for anatomical variations that might affect airflow. Patients who had undergone previous airway surgery, had central sleep apnea, or exhibited muscular or joint injuries in the head-and-neck region were excluded. We enrolled 18 males and 1 female diagnosed with positional OSA on overnight PSG (Table 1). The research protocol was reviewed and approved by our Institutional Review Board (IRB approval number 2018-11).

**PSG and recording of snoring**

Overnight PSG (EMBLA Embletta MPR-PG; Natus Medical, Pleasanton, CA, USA) was performed for each patient by the same PSG specialist. Electroencephalography, bilateral electro-oculography, and submental electromyography were used to determine sleep stage. Oronasal airflow was monitored by a thermistor. Thoracoabdominal respiratory effort was measured using a respiratory sensor placed over the rib case and abdomen. Oxyhemoglobin saturation was recorded using a finger pulse oximeter. Body position during sleep, recorded by a sensor, was classified into five categories: supine, right and left lateral, prone, or upright. All data were recorded on a personal computer.

**Recording of snoring and acoustic analysis**

Once PSG had commenced, we recorded all snoring sounds and body positions. A microphone was suspended 1.5 m above the bed. We recorded three snoring sounds immediately after apnea, which were analyzed phonetically and averaged. The sounds were digitized and edited according to sleep stage [non-rapid eye movement (NREM) vs. rapid eye movement (REM)] and sleep position (supine vs. both lateral positions). The sounds were analyzed using Praat software (ver. 5.2.16; http://www.praat.org). The sampling rate was converted to 44100 Hz. We measured differences in sound intensity (dB), spectrographs, and formant frequencies between patients in the supine and both lateral positions.

**Statistical analysis**

We used a linear regression model and the paired t-test to assess correlations among changes in snoring intensity, the AHI, and formant frequencies. All tests were performed using SPSS software (ver. 25.0; IBM Corp., Armonk, NY, USA). A p-value <0.05 was considered to indicate statistical significance.

**Results**

**Snoring intensity**

Table 2 shows the snoring intensity by sleep position and other parameters. We found no significant correlation of snoring intensity with the AHI, respiratory disturbance index (RDI),...
Next, we assessed changes in snoring according to a change in sleep position, from supine to lateral. In general, the snoring intensity decreased when the sleep position changed from supine to lateral. Five patients whose snoring completely disappeared were excluded from the analysis. We found significant negative correlations of the AHI and RDI with difference of snoring sound intensity when sleep position changed from supine to lateral position. Lower AHI and RDI values in positional OSA patients were associated with a larger decrease in snoring when the sleep position changed from supine to lateral (Table 3, Fig. 1).

Formant frequencies of snoring
Of the 19 patients, the snoring sounds of 13 were analyzed in terms of formant frequency; 5 patients whose snoring disappeared completely, and 1 whose snoring sounds could not be analyzed because of a recording error, were excluded from the analysis. A paired t-test was performed to confirm the change in each formant frequency according to the change in sleep position (supine to lateral). Formant frequencies 1 (F1), F3, and F4 were significantly decreased (p-value: 0.02, 0.03, and 0.01, respectively). The reduction in F2 was not statistically significant (Table 4). Fig. 2 shows the frequency change in each patient.

Discussion
The first report of OSA therapy based on sleep position appeared in 1982. Many subsequent studies confirmed that a change in sleep position from supine to lateral reduced the incidence of respiratory events. Patients with an increase in the rate of respiratory events (apnea or hypopnea) at least two-fold higher in the supine than in the lateral position are diagnosed with positional OSA, this type of OSA accounts for more than half of all OSA cases. To the best our knowledge, this study is the first to describe changes in snoring and formant frequency when patients with positional OSA change their sleep position. Koutsourelakis, et al. showed that snoring tended to be louder during NREM than REM sleep. In particular, the snoring time was longest, and the snoring inten-
Changes in snoring intensity and formant frequency by sleep position

Koh TK, et al.

Sup.: supine position, Lat.: lateral position, ΔSnoring intensity: change in snoring intensity from the supine to the lateral position.

Table 4. Changes in formant frequency by sleep position

|       | Sup. Mean ± SD (Hz) | Lat. Mean ± SD (Hz) | Difference of mean value (Sup.-Lat.) | p-value |
|-------|--------------------|--------------------|-------------------------------------|---------|
| F1    | 868.4 ± 191.3      | 733.1 ± 153.1      | 135.3                               | 0.02    |
| F2    | 1681.7 ± 320.4     | 1648.5 ± 149.5     | 33.2                                | 0.74    |
| F3    | 3002.5 ± 310.6     | 2847.5 ± 137.4     | 155.0                               | 0.03    |
| F4    | 4235.2 ± 145.3     | 4098.7 ± 110.1     | 136.5                               | 0.01    |

F1, F2, F3, and F4: first, second, third, and fourth formant frequencies, respectively. Statistical significance: p < 0.05. Sup.: supine position, Lat.: lateral position, SD: standard deviation

Correlations between changes in snoring and the RDI and AHI. RDI: respiratory disturbance index, AHI: apnea-hypopnea index, Fig. 1.

Nakano, et al. described an effect of body position on snoring intensity highest, in NREM stage 3 (N3). When the sleep posture changed from supine to lateral, snoring disappeared in 5 patients, decreased in 10, and increased in 3. All patients whose snoring disappeared had AHIs of less than 15, and all those whose snoring increased had AHIs greater than 40. Snoring tended to decrease when patients with AHIs of 15–40 assumed a lateral position (the lower the AHI, the greater the decrease). Nakano, et al. described an effect of body position on snoring in apneic and nonapneic snorers. Nonapneic (but not apneic) snoring intensity decreased when the sleep position changed from supine to lateral, whereas snoring was unvoiced, as the sound is created in the laryngeal and supralaryngeal regions, not by the vocal cords. In addition, the airway affects the energy transfer at a particular frequency. The resonance frequency allowing the maximal energy transfer is the formant frequency (F). However, because snoring sounds are caused by pharyngeal structures, not the vocal cords, speech analysis techniques are of limited use. Nevertheless, the formant frequency has been determined in several studies that analyzed the acoustic characteristics of snoring sounds, such that the same analysis was performed in the present study.

F1 reflects the extent of pharyngeal constriction and the height of the tongue. F2 is related to the degree of advancement of the tongue relative to its neutral position, where the frequency increases as the retrolingual space increases. F3 correlates with the degree of lip-rounding. F4 is related to the location and shape of the larynx and laryngeal ventricle, but there is as yet no general consensus on the precise relationship. F1 and F2 can be used to distinguish among the vowels, whereas F3 and F4 are related to the individual timbre.

We evaluated the change in formant frequency (F1–F0) according to the change in sleep position, except in patients whose snoring disappeared in the lateral position. Statistically sig-
Significant decreases were determined in $F_1$, $F_3$, and $F_4$. These results indicate that a change in sleep position from supine to lateral increases the tongue height, widens the pharynx and causes a change in lip shape to non-circular. In the case of $F_2$, the frequency increased in patients with decreased snoring intensity and decreased in those with increased snoring intensity (147.51 vs. -439.85 Hz), although the changes were not statistically significant. These observations suggest that when the sleep position is changed from supine to lateral in those with decreased snoring intensity, the position of the tongue is advanced relative to the neutral position and the retrolingual space is widened. However, according to the formula used to obtain the formant frequency, $F_n = \frac{(2n-1)C}{4L}$ (where $n$ is a number from 1-4, $F_n$ is the formant frequency, $C$ is the velocity of sound in the air, and $L$ is the length of vocal tract), the change in sleep position causes a change in the vibrating site of the upper airway where the snoring sound is created, which in turn changes $L$.

The principal limitation of this study was that relatively few patients were included; therefore, we could not stratify the analyses by AHI. OSA is classified as mild, moderate or severe based on the AHI. We could not statistically compare changes in snoring intensity and formant frequency between OSA subgroups, nor explore gender differences, due to the small number of patients. Also, the time and intensity of snoring sounds are known to differ depending on the sleep stage. In a previous study, N3 had the longest snoring time, followed by N2, REM, and N1. N3 also had the largest snoring intensity, followed by N2, N1, and REM. However, a limitation of our study was that the NREM stage was not further stratified.

OSA treatment is initially conservative, and includes weight loss and cessation of alcohol intake followed by continuous positive airway pressure therapy, oral appliance therapy, and sleep surgery. Positional OSA patients can also use devices that prohibit the supine sleep position. However, our data showed that although positional therapy may reduce the incidence of respiratory events in OSA patients, the effect on snoring may differ depending on the AHI and RDI. Therefore, when applying positional therapy, it should be recognized that its purpose is not to decrease snoring, but rather to decrease the incidence of respiratory events.

In conclusion, when the sleep posture changed from supine to lateral in patients with positional OSA, snoring sounds were reduced, with the extent of the reduction depending on the AHI, and the formant frequency decreased.
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Author Contribution

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