

Effects of Mandibular Advancement on Supine Airway Size in Normal Subjects During Sleep

Shigetoshi Hiyama, DDS, PhD; Satoru Tsuiki, DDS, PhD; Takashi Ono, DDS, PhD; Takayuki Kuroda, DDS, PhD; Kimie Ohyama, DDS, PhD

Maxillofacial Orthognathics, Graduate School, Tokyo Medical and Dental University

Study Objectives: To examine changes in the upper-airway dimension and its surrounding structures induced by mandibular advancement during sleep.

Design: Eleven nonapneic adult males participated in the study. A set of supine lateral cephalograms was taken for each subject at the end of expiration during stage 1 and 2 non-rapid-eye-movement sleep with and without a Klearway™ appliance (Great Lakes Orthodontics, NY, USA), which was adjusted to 67% of the maximum protrusion position. The Wilcoxon signed-rank test was used to compare changes in the anteroposterior width of the upper airway and the positions of the hyoid bone and third cervical vertebra with and without the appliance.

Setting: N/A

Patients or Participants: N/A

Interventions: N/A

Measurements and Results: The amount of jaw opening was significantly increased by wearing the titratable oral appliance, and the mandibular symphysis moved backward. The sagittal dimension of the

superior pharyngeal airway was significantly increased; however, no significant changes were found in the middle and inferior pharyngeal airway. Significant posterior displacement of the hyoid bone and third cervical vertebra was seen. Moreover, significant inferior displacement of the hyoid bone was also seen. The relationship among the mandibular symphysis, the hyoid bone, and the third cervical vertebra remained constant.

Conclusions: Mandibular advancement significantly increases the size of the upper airway in the velopharynx and results in posteroinferior displacement of the hyoid bone and posterior displacement of the third cervical vertebra during sleep.

Key Words: Obstructive sleep apnea (OSA); upper airway; mandibular advancement; titratable oral appliance; Klearway™; supine lateral cephalogram; sleep

Citation: Hiyama S, Tsuiki S, Ono T et al. Effects of mandibular advancement on supine airway size in normal subjects during sleep. *SLEEP* 2003; 26(4):440-445.

INTRODUCTION

ORAL APPLIANCES HAVE BEEN WIDELY USED IN THE TREATMENT OF PATIENTS WITH OBSTRUCTIVE SLEEP APNEA (OSA) to dilate the upper airway and to prevent upper-airway obstruction during sleep by holding the mandible in the forced protruded position.¹ Many previous studies have evaluated the effects of various types of oral appliances based on overnight polysomnographic recording²⁻¹⁶ and have found that oral-appliance therapy can be effective, especially in the treatment of mild to moderate OSA.

To investigate the mechanism of this effect, prior studies have examined the effect of mandibular-advancement devices on upper-airway configuration in healthy subjects or OSA patients during wakefulness.^{2,3,5,6,9,10,12,13,17-19} Potentially of greater relevance would be the influence of these devices upon identical measurements during sleep when upper-airway obstruction occurs in OSA patients.

The purpose of this study was to evaluate changes in the upper-airway dimension and its surrounding structures in response to a protruded mandibular position in normal subjects during sleep.

Disclosure Statement

This study was supported by a Grant-in-Aid for Scientific Research (No.10307052) from the Japanese Ministry of Education, Science, Sports and Culture.

Submitted for publication July 2002

Accepted for publication February 2003

Address correspondence to: Shigetoshi Hiyama, DDS, PhD; Maxillofacial Orthognathics, Graduate School, Tokyo Medical and Dental University, 5-45 Yushima 1-chome, Bunkyo-ku, Tokyo, 113-8549 Japan; Tel: +81-3-5803-5536; Fax : +81-3-5803-0203; E-mail : s-hiyama@syd.odn.ne.jp

MATERIALS AND METHODS

Subjects

Eleven nonapneic adult males participated in this study [age: 28.5±1.6 (mean±SD) years, body mass index: 22.4±2.4 kg/m²]. All of the participants had adequate dentition (>14 teeth in each of the maxillary and mandibular arches) with a skeletal Class I relationship and were confirmed to have no medical history of temporomandibular disorders or sleep-disordered breathing such as snoring or apnea. Before the study, all of the subjects gave their informed consent to participate after receiving a full explanation of the aim and design of this study.

Experimental procedures

Eleven Klearway™ oral appliances (Great Lakes Orthodontics, NY, USA)¹⁹ were fabricated on plaster casts of the maxillary and mandibular dental arches, and a wax bite was registered at the most-retruded mandibular position. The maxillary and mandibular components of the titratable oral appliance are made from thermoactive acrylic resin, which not only firmly fits on the dentition, but also has flanges that extend to undercut areas of the alveolar bone. The two arch components are connected with an adjustable-screw mechanism positioned close to the palatal arch. The screw mechanism enables anteroposterior mandibular movement over a range of 11.0 mm in a total of 44 increments of 0.25 mm. The titratable oral appliance allows significant retention and reliable titration and decreases teeth soreness and soft-tissue discomfort. An atypical experimental vertical separation of 5 mm instead of the standard clinical separation of 2 mm was obtained at the maxillary and mandibular incisors so as to not interfere with smooth forward displacement of the mandible from the most-retruded position to maximum protrusion when the titratable oral appliance was in place.

Silver/silver chloride surface electrodes (NE-155A; Nihon Kohden, Tokyo, Japan) to record electroencephalograms (C3/A2 of the international 10-20 system) to determine the sleep stage were positioned with

paste (Cardio cream Z-101BC: Nihon Kohden, Tokyo, Japan). The ground electrode was attached to the right earlobe. The signals were amplified (dual-channel bioelectric amplifier MEG-2100: Nihon Kohden, Tokyo, Japan) and monitored on an oscilloscope (Handy monitor VC-22: Nihon Kohden, Tokyo, Japan). Low- and high-pass filters were set at 0.5 Hz and 30 Hz, respectively. The sweep velocity of the oscilloscope was set at 25 mm per second. A thermistor (TR-712T: Nihon Kohden, Tokyo, Japan) to detect nasal airflow was attached to the right nostril, and amplified signals were monitored simultaneously with the electroencephalogram on the oscilloscope.

Each subject was asked to lie on a cushioned table in the supine position with the head supported by a pillow. The cephalostat for the table enabled the head of the subject to be fixed without pain or discomfort by inserting ear rods to the bilateral external auditory meatuses. The focus-

film distance and object-film distance were adjusted to 170 cm and 20 cm, respectively. The exposure factors—including the tube voltage, the tube current, and the exposure time—were set at 95 kVp and 5 mAs. Details of the roentgenographic equipment used to take supine lateral cephalograms have been reported previously.²⁰

The room light was turned off, and the subject was asked to fall asleep without the titratable oral appliance. A supine lateral cephalogram was then taken at the end of expiration during stage 1 and 2 non-rapid-eye-movement (NREM) sleep. The room light was then turned on, and the subject was awakened to fit the oral appliance, which was adjusted to 67% of the maximum protrusion (MAX) position without removing the ear rods. The subject was then asked to sleep again, and a supine lateral cephalogram with the titratable oral appliance was taken in the same manner. The 67% MAX position was employed in this study because the mandibular position is widely used for the treatment of OSA patients and was recently demonstrated to be suitable to obtain the same effect as the MAX position in terms of anteroposterior dimension of the velopharynx.¹⁹

Data analysis

Lateral cephalograms of each subject were traced and superimposed on the sella-nasion plane, registered at the sella by an experienced orthodontist. A detailed description of the supine cephalometric protocol is given in Figure 1. The Wilcoxon signed-rank test was used to compare differences with and without the titratable oral appliance for each variable. P-values less than 0.05 were considered statistically significant.

The measurement reproducibility in the supine lateral cephalograms evaluated, based on the method error for each cephalometric variable, and a repeatability test to determine the reproducibility of the mandibular posture, upper-airway dimension, and related structures during sleep have been reported previously.²¹

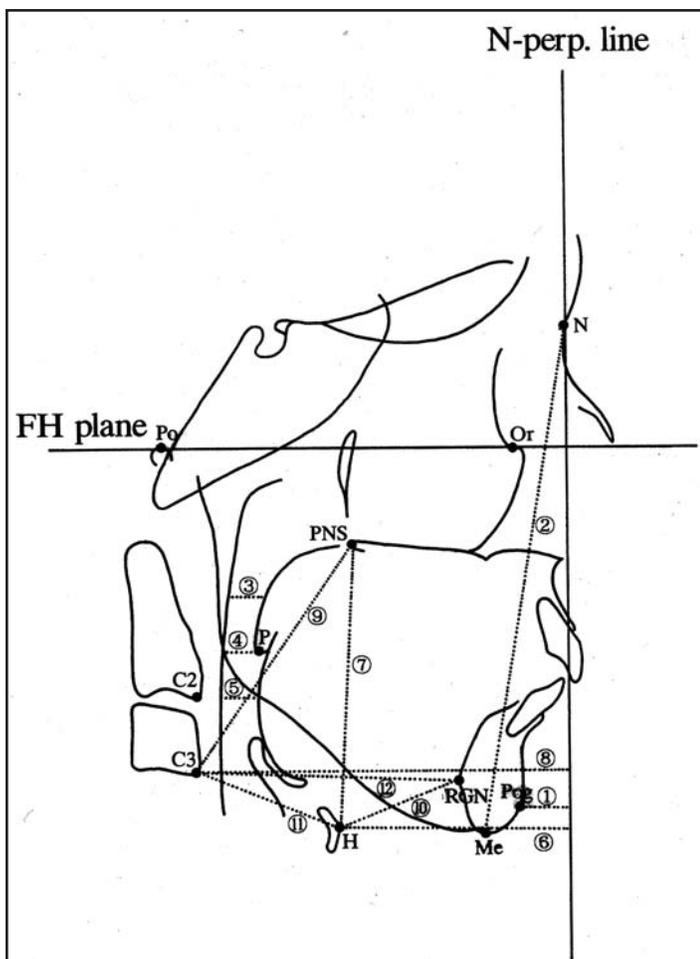


Figure 1—Diagrammatic representation of anatomic points and lines used to identify cephalometric variables. N: the most anterior point of the frontonasal suture in the midsagittal plane, Or: the lowest point in the inferior margin of the orbit, Po: the superior point of the external auditory meatus, PNS: the posterior nasal spine, Pog: the most anterior point of the bony chin in the midsagittal plane, RGN: the most posterior point on the mandibular symphysis, Me: the most inferior midline point on the mandibular symphysis, H: the most superoanterior point on the body of the hyoid bone, P: the tip of the soft palate, C2: the most inferoanterior point on the body of the second cervical vertebra, C3: the most inferoanterior point on the body of the third cervical vertebra, FH plane (Frankfort horizontal plane): the line through Or and Po, N-perp. line: the line perpendicular to the FH plane through N (1) N-perp. to Pog: the distance between the N-perp. line and Pog (when Pog is anteriorly positioned relative to the N-perp. line, this value is considered positive), (2) N-Me: the distance between N and Me, (3) SPPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the soft palate on a line parallel to the FH plane that runs through the middle of the line from PNS to P, (4) MPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the tongue on a line parallel to the FH plane that runs through P, (5) IPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the tongue on a line parallel to the FH plane that runs through C2, (6) N perp. to H: the distance between the N perp. line and H, (7) PNS-H: the distance between PNS and H, (8) N perp. to C3: the distance between the N perp. line and C3, (9) C3-PNS: the distance between C3 and PNS, (10) H-RGN: the distance between H and RGN, (11) C3-H: the distance between C3 and H, (12) C3-RGN: the distance between C3 and RGN

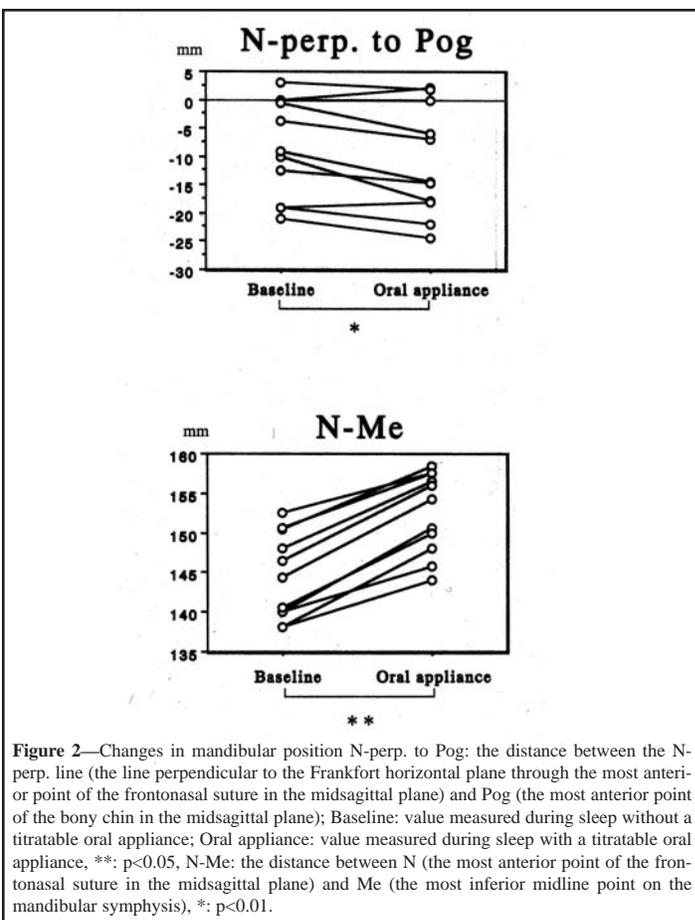


Figure 2—Changes in mandibular position N-perp. to Pog: the distance between the N-perp. line (the line perpendicular to the Frankfort horizontal plane through the most anterior point of the frontonasal suture in the midsagittal plane) and Pog (the most anterior point of the bony chin in the midsagittal plane); Baseline: value measured during sleep without a titratable oral appliance; Oral appliance: value measured during sleep with a titratable oral appliance, *: $p < 0.05$, N-Me: the distance between N (the most anterior point of the frontonasal suture in the midsagittal plane) and Me (the most inferior midline point on the mandibular symphysis), **: $p < 0.01$.

RESULTS

With regard to changes in the anteroposterior position of the mandible, the N-perp. to Pog distance (please see list of definitions) was significantly decreased by wearing the titratable oral appliance, which indicated that the mandibular symphysis was moved backward (by 2.6 ± 3.0 mm) by wearing the oral appliance during sleep. With regard to vertical mandibular positional changes, the N-Me distance was significantly increased by wearing the titratable oral appliance (Figure 2).

The sagittal dimension of the superior pharyngeal airway (SPPS) was significantly increased (by 1.2 ± 1.6 mm) by wearing the titratable oral appliance (Figure 3). In contrast, the sagittal dimensions of the middle (MPS) and inferior (IPS) pharyngeal airways did not show any significant changes.

Since there was a wide range of baseline airway size, changes in the upper-airway dimension related to wearing the titratable oral appliance were calculated in terms of a percentage of baseline. Figure 4 shows the relationship between the baseline airway size and the percentage change. In the SPPS, a significant correlation coefficient was demonstrated, which meant that the smaller airway showed more dramatic change than did the bigger airway. On the other hand, no significant correlation coefficients were found in the MPS and IPS.

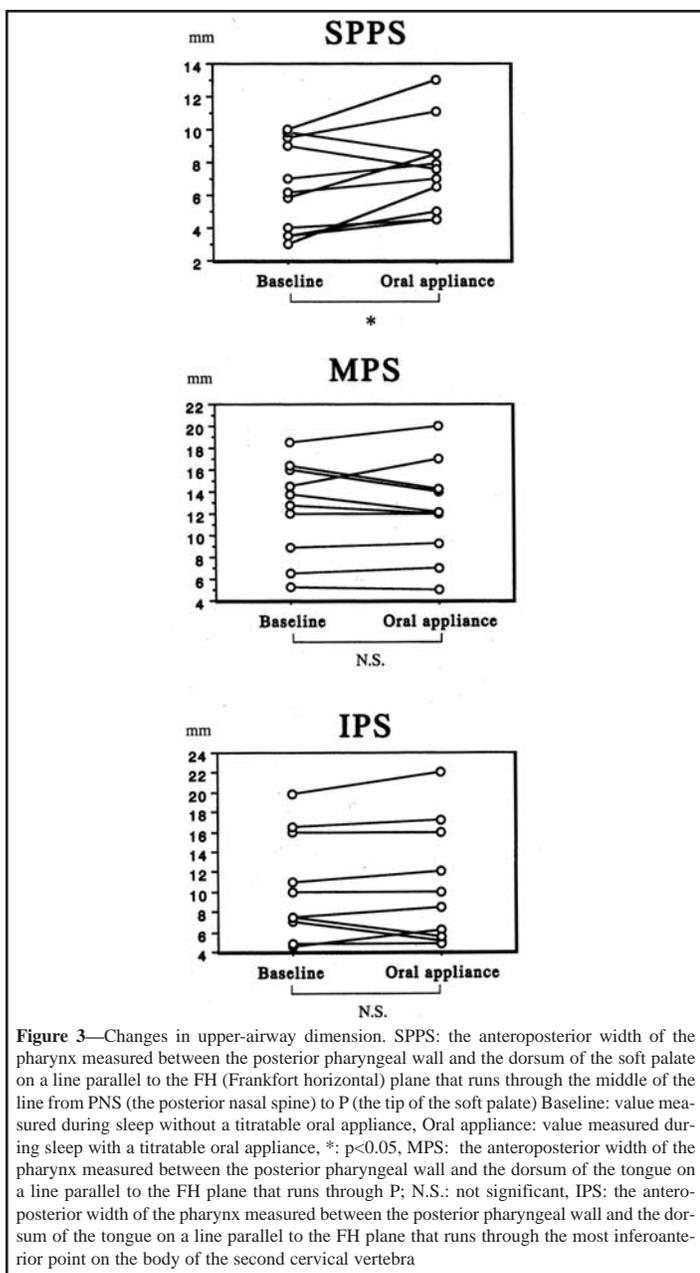


Figure 3—Changes in upper-airway dimension. SPPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the soft palate on a line parallel to the FH (Frankfort horizontal) plane that runs through the middle of the line from PNS (the posterior nasal spine) to P (the tip of the soft palate) Baseline: value measured during sleep without a titratable oral appliance, Oral appliance: value measured during sleep with a titratable oral appliance, *: $p < 0.05$, MPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the tongue on a line parallel to the FH plane that runs through P; N.S.: not significant, IPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the tongue on a line parallel to the FH plane that runs through the most inferoanterior point on the body of the second cervical vertebra

The N-perp. to H distance was significantly increased by wearing the titratable oral appliance, which was related to posterior displacement of the hyoid bone (Figure 5). The hyoid bone moved backward by 1.7 ± 1.7 mm. In addition, significant inferior movement of the hyoid bone was also seen. Both the N-perp to C3 and C3-PNS distances were significantly increased by wearing the oral appliance (by 1.4 ± 1.2 mm and 0.9 ± 0.8 mm, respectively), which reflected posterior displacement of the third cervical vertebra (Figure 5). The relationship among the mandibular symphysis, the hyoid bone, and the third cervical vertebra remained constant (Figure 6). Figure 7 shows typical changes with and without the titratable oral appliance in 1 subject. Backward rotation of the mandible, an increase in the retropalatal airway, and posteroinferior movement of the hyoid bone are shown.

DISCUSSION

In this study, we have shown that the use of a titratable oral appliance set at 67% MAX position results in significant increase in the superior

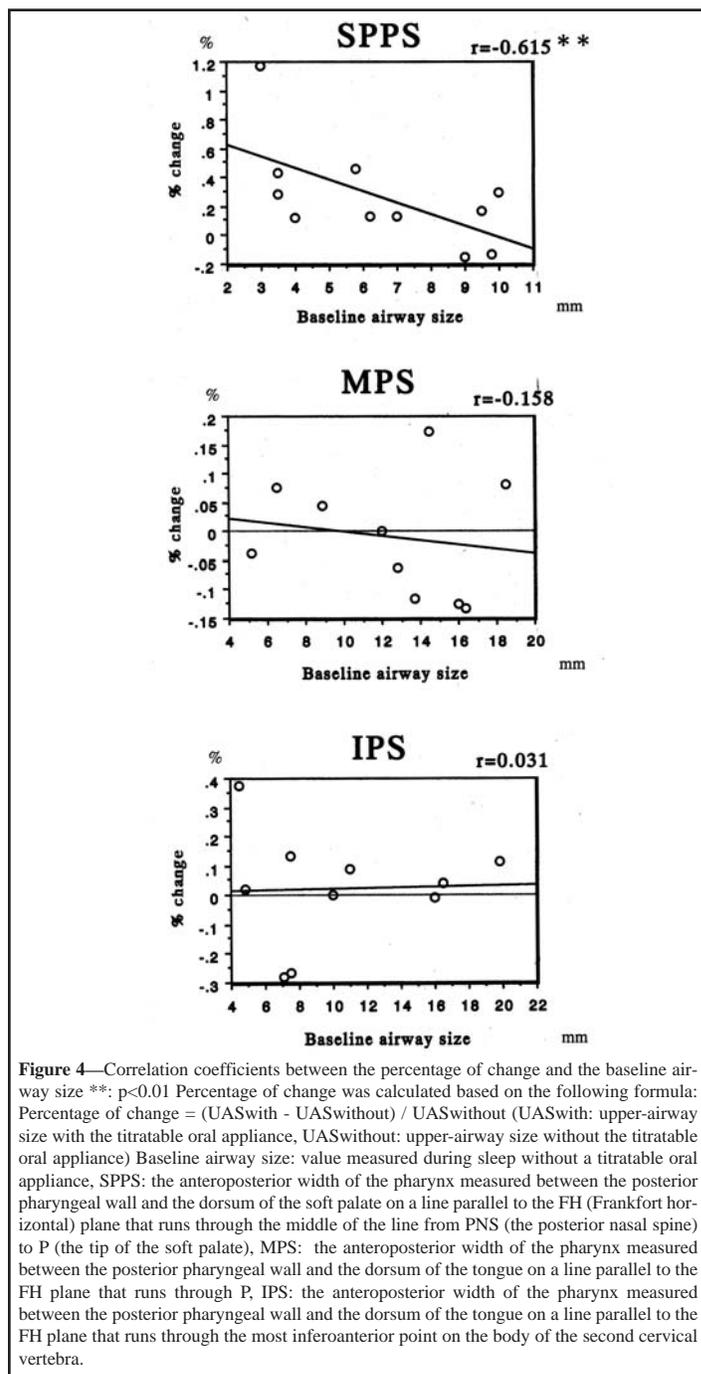


Figure 4—Correlation coefficients between the percentage of change and the baseline airway size **: $p < 0.01$ Percentage of change was calculated based on the following formula: Percentage of change = (UASwith - UASwithout) / UASwithout (UASwith: upper-airway size with the titratable oral appliance, UASwithout: upper-airway size without the titratable oral appliance) Baseline airway size: value measured during sleep without a titratable oral appliance, SPPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the soft palate on a line parallel to the FH (Frankfort horizontal) plane that runs through the middle of the line from PNS (the posterior nasal spine) to P (the tip of the soft palate), MPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the tongue on a line parallel to the FH plane that runs through P, IPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the tongue on a line parallel to the FH plane that runs through the most inferoanterior point on the body of the second cervical vertebra.

upper-airway dimension, inferoposterior displacement of the mandible and hyoid bone, and posterior movement of the third cervical vertebra.

Mandibular Position

The results of this study demonstrated that the N-Me distance during sleep with the titratable oral appliance was significantly greater than the distance during sleep without the appliance, which indicated jaw opening with insertion of the titratable oral appliance. When we fabricated the titratable oral appliance, we had to raise the occlusal vertical dimension. An atypical experimental vertical separation of 5 mm instead of the standard clinical separation of 2 mm was obtained at the maxillary and mandibular incisors so as to not interfere with smooth forward displacement of the mandible from the most-retruded position to maximum protrusion when the titratable oral appliance was in place. It would be desirable to minimize the amount of bite opening in fabricating the titratable oral appliance; however, even a minimal increase in the occlusal vertical dimension while fabricating the appliance would result in a significant increase in the N-Me distance. In general, an increase in the occlusal vertical dimension (ie, backward rotation of the mandible) is well recognized to have a close geometric relationship with the anteroposterior position of the mandibular symphysis. Therefore, the posterior displacement of Pog observed in this study could be related to such backward rotation of the mandible.

Upper-airway Dimension

In this study, the SPPS was significantly increased by wearing the titratable oral appliance, whereas no significant changes were seen in the MPS or IPS upper-airway dimensions. Previous studies on changes in the upper-airway dimension related to mandibular advancement were conducted in healthy subjects or OSA patients during wakefulness; it would be interesting to compare them with the results in the present study, which was conducted while the subjects were asleep. A significant increase in the velopharynx or retropalatal region related to mandibular

advancement was observed in all of the previous studies except for that by Ferguson et al.¹⁸ Meanwhile, a significant increase was seen only in the SPSS during sleep in the present study, which indicated that the response of the upper airway to mandibular advancement during sleep is similar to that while awake. It has been reported that the activity of pharyngeal muscles, including the upper-airway-dilating muscles, is not attenuated during sleep compared to that during wakefulness in normal men.²²⁻²⁴ Since the subjects in the present study were normal adults without sleep-disordered breathing, this property of the upper-airway-dilating muscles might be related to the similar response of the upper airway to mandibular advancement in wakefulness and sleep.

It is unclear why a significant increase was found only in the velopharynx, whereas no significant changes were detected in the oropharynx or hypopharynx with mandibular advancement. If the mandible could be advanced in a direction perpendicular to the posterior pharyngeal wall, the anterior pharyngeal wall, which consists of the soft palate and tongue dorsum, could move in the same direction, which would result in equally notable increases in the superior, middle, and inferior upper-airway dimensions. However, in reality, the occlusal vertical dimension must be increased when one fabricates the titratable oral appliance to avoid interference between the maxillary and mandibular incisors. Therefore, the change in the mandibular position after wearing the oral appliance becomes backward rotation rather than anterior displacement. Indeed, there was a significant decrease in the N-perp. to Pog distance regardless of mandibular advancement in this study. As a con-

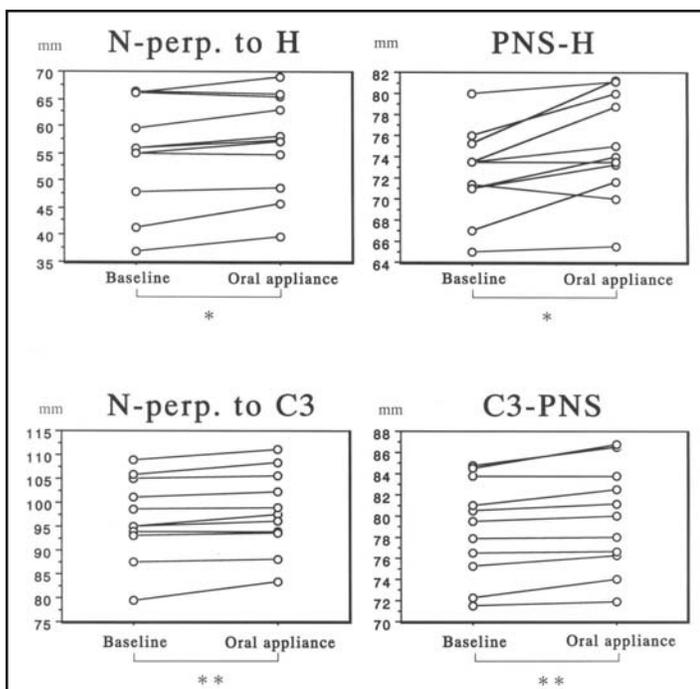


Figure 5—Changes in the positions of the hyoid bone and cervical vertebra. **: $p < 0.05$. N perp. to H: the distance between the N perp. line (the line perpendicular to the Frankfort horizontal plane through the most anterior point of the frontonasal suture in the midsagittal plane) and H (the most superoanterior point on the body of the hyoid bone), Baseline: value measured during sleep without a titratable oral appliance, Oral appliance: value measured during sleep with a titratable oral appliance, *: $p < 0.01$, PNS-H: the distance between PNS (the posterior nasal spine) and H, N perp. to C3: the distance between the N perp. line and C3 (the most inferoanterior point on the body of the third cervical vertebra); C3-PNS: the distance between C3 and PNS

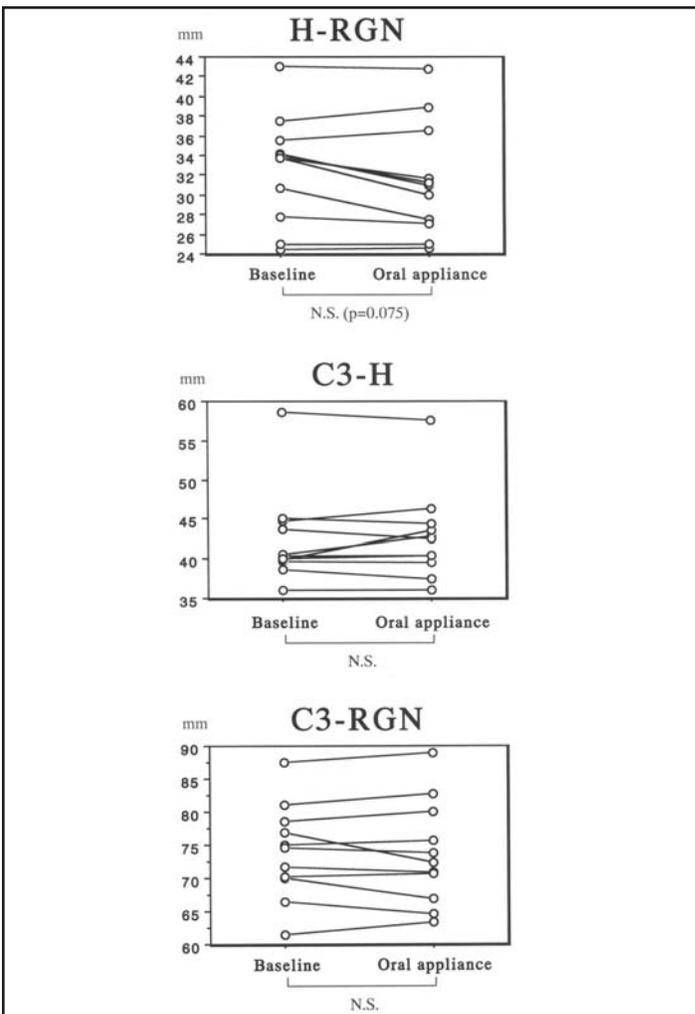


Figure 6—Changes in the relationship among the hyoid bone, cervical vertebra and mandible. H-RGN: the distance between H (the most superoanterior point on the body of the hyoid bone) and RGN (the most posterior point on the mandibular symphysis), Baseline: value measured during sleep without a titratable oral appliance, Oral appliance: value measured during sleep with a titratable oral appliance, N.S.: not significant, C3-H: the distance between C3 (the most inferoanterior point on the body of the third cervical vertebra) and H; C3-RGN: the distance between C3 and RGN

sequence of mandibular advancement combined with backward rotation, no significant changes were observed in the MPS or IPS dimensions, while the SPPS dimension was significantly increased. From this point of view, the increase in the occlusal vertical dimension should be minimized in fabricating the titratable oral appliance. Isono et al²⁵ demonstrated that anterior movement of the mandible widened the velopharyngeal airway and discussed 2 possible mechanisms for improving velopharyngeal airway patency. First, anterior displacement of the mandible may increase the transmural pressure at the velopharynx, which can lead to a larger cross-sectional area in this region. Second, mandibular advancement may stabilize the airway and reduce the collapsibility of the velopharynx.²⁵

In a previous study, it was demonstrated that the onset of an apneic episode was associated with closure of the upper airway at the velopharyngeal level.^{26,27} Moreover, in a magnetic resonance imaging study using healthy subjects, Trudo et al²⁸ showed that the upper-airway dimension tended to decrease in both the retropalatal and retroglossal regions during sleep; the former showed more dramatic changes than the latter. Therefore, dilation in the velopharyngeal region during sleep could prevent the occurrence of OSA and lead to an improvement of symptoms.

Changes in the Positions of the Hyoid Bone and Cervical Vertebra and Their Relationships with the Mandible

Posteroinferior displacement of the hyoid bone was observed when the mandible was advanced (Figure 5). The hyoid bone is closely connected to both the cranial and mandibular bones through the suprahyoid muscles. Thus, it is likely that the position of the hyoid bone is influenced by mandibular position and head posture. Therefore, the change in the position of the hyoid bone observed in this study might be related to the backward rotation of the mandible.

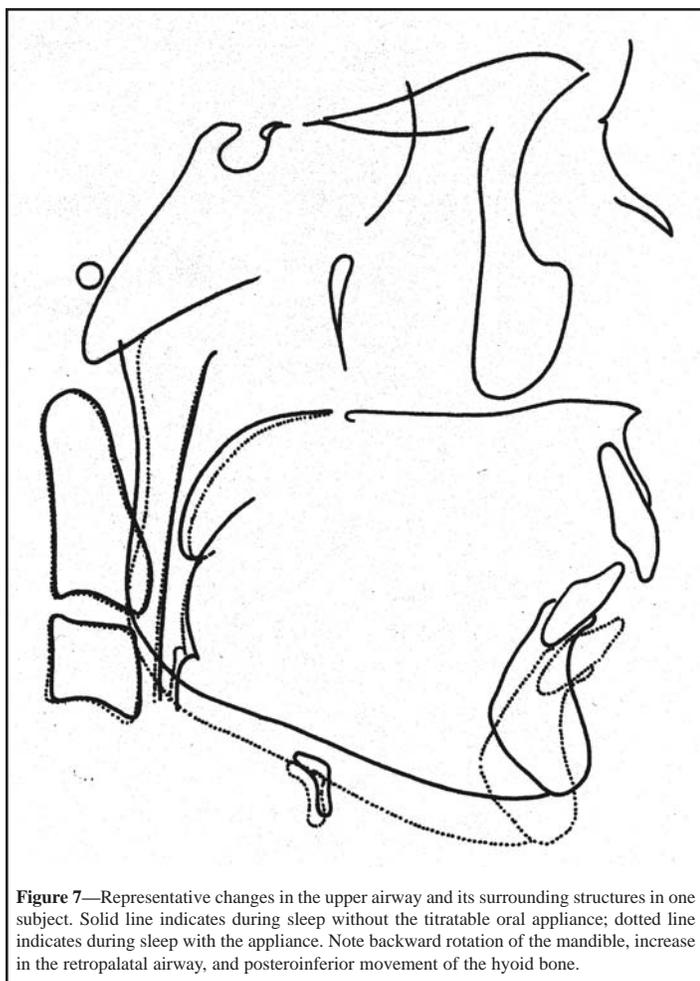


Figure 7—Representative changes in the upper airway and its surrounding structures in one subject. Solid line indicates during sleep without the titratable oral appliance; dotted line indicates during sleep with the appliance. Note backward rotation of the mandible, increase in the retropalatal airway, and posteroinferior movement of the hyoid bone.

On the other hand, the hyoid bone is considered to play an important role in maintaining the upper airway.^{29,30} A posteroinferior change in the position of the hyoid bone is generally recognized to be related to a decrease in the upper-airway dimension. However, measurements of the upper-airway dimension showed no significant reductions (Figure 3). This suggests that the posteroinferior change in the position of the hyoid bone should be interpreted so that the upper airway could be fully maintained even if the hyoid bone moved posteroinferiorly. Thus, the upper airway was fully maintained without forced forward positioning of the hyoid bone when the mandible was positioned anteriorly, and this finding seemed to indirectly reflect the effect of the appliance.

When the mandible was advanced, the third cervical vertebra moved backward (Figure 5). Since the hyoid bone simultaneously moved in the same direction, the distance between the third cervical vertebra and hyoid bone (C3-H) remained constant (Figure 6). The C3-H distance, which is closely related to the sagittal dimension of the upper airway, has been shown to be stable independent of external disturbances, including mandibular set-back surgery for the treatment of mandibular prognathism.^{31,32} The finding that the distance between the hyoid bone and cervical vertebra remained constant suggests that a mechanism for protecting the upper airway may have been present in our subjects.

The clockwise rotation of the mandible observed in this study can result in backward movement of the Pog and RGN geometrically. Since the hyoid bone and cervical vertebrae, as well as the RGN, moved constantly backward with the titratable oral appliance, no changes were observed in the distances among these structures (Figure 6).

Methodology

A few studies have examined the upper-airway morphology using supine lateral cephalograms.^{33,34} Since it has been demonstrated that upper-airway morphology and tongue posture are dependent on body position,^{35,36} the effect of body position must be taken into account in discussing the upper-airway dimension. Thus, the supine body position, one of the most popular sleep postures,³⁷ was adopted in this study. It has been shown that the tonus of jaw-closing muscles is reduced during sleep, depending on the sleep stage.^{22,38} Miyamoto et al³⁹ reported that the mandibular position during sleep in healthy adults was significantly affected by the sleep stage. Therefore, lateral cephalograms in this study were taken in stage 1 and 2 NREM sleep, which was defined by the electroencephalogram. When the waking pattern of rhythmic alpha activity was attenuated, the subject was judged to have fallen into stage 1 NREM sleep, and a supine lateral cephalogram was taken at that time. Frequently, stage 1 NREM sleep continued for only a short period of time, and it was often difficult to take a supine lateral cephalogram during stage 1 NREM sleep. In these cases, we took a supine lateral cephalogram during stage 2 NREM sleep, which could be clearly determined based on 2 specific patterns: the sleep spindle and the K complex. In addition, it has been reported that the position and shape of the oropharyngeal soft and hard tissues change in association with the respiratory phase.⁴⁰⁻⁴² This suggests that the respiratory phase must be carefully determined to evaluate the oropharyngeal morphology. Therefore, all cephalometric radiographs in this study were taken at the end of expiration.

CONCLUSIONS

The results of this study suggest that mandibular advancement may preserve upper-airway patency during sleep in normal male adults by maintaining an enlarged upper-airway size, particularly in the velopharyngeal region. However, we can recognize some limitations in the experimental design of the present study: the influence of the sleep stage and gender differences. In addition, a major limitation might be that the subjects were normal adults, not OSA patients. Although we should be careful in predicting the possible effect of mandibular advancement on the upper-airway dimension in OSA patients based on these results, our results suggest that the upper airway in OSA patients may be signifi-

cantly enlarged with mandibular advancement during sleep.

ACKNOWLEDGEMENTS

The authors are grateful to all of the subjects in this study. We are also indebted to Mr. T. Chiba for his technical assistance in radiography. This study was supported by a Grant-in-Aid for Scientific Research (No.10307052) from the Japanese Ministry of Education, Science, Sports and Culture.

DEFINITIONS

C2: the most inferoanterior point on the body of the second cervical vertebra

C3: the most inferoanterior point on the body of the third cervical vertebra

FH plane: Frankfort horizontal plane—the line through Or and Po

Me: the most inferior midline point on the mandibular symphysis

H: the most superoanterior point on the body of the hyoid bone

N: the most anterior point of the frontonasal suture in the midsagittal plane

N-perp. line: the line perpendicular to the FH plane through N

Or: the lowest point in the inferior margin of the orbit

P: the tip of the soft palate

PNS: the posterior nasal spine

Po: the superior point of the external auditory meatus

Pog: the most anterior point of the bony chin in the midsagittal plane

RGN: the most posterior point on the mandibular symphysis

C3-PNS: the distance between C3 and PNS

C3-H: the distance between C3 and H

C3-RGN: the distance between C3 and RGN

H-RGN: the distance between H and RGN

IPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the tongue on a line parallel to the FH plane that runs through C2

MPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the tongue on a line parallel to the FH plane that runs through P

N perp. to C3: the distance between the N perp. line and C3

N perp. to H: the distance between the N perp. line and H

N-perp. to Pog: the distance between the N-perp. line and Pog (when Pog is anteriorly positioned relative to the N-perp. line, this value is considered positive)

N-Me: the distance between N and Me

PNS-H: the distance between PNS and H

SPPS: the anteroposterior width of the pharynx measured between the posterior pharyngeal wall and the dorsum of the soft palate on a line parallel to the FH plane that runs through the middle of the line from PNS to P

REFERENCES

- Schmidt-Nowara W. Recent development in oral appliance therapy of sleep disordered breathing. *Sleep Breath* 1999;3:103-6.
- Bonham PE, Currier GF, Orr WC, Othman J, Nanda RS. The effect of a modified functional appliance on obstructive sleep apnea. *Am J Orthod Dentofac Orthop* 1988;94:384-92.
- Schmidt-Nowara WW, Meade TE, Hays MB. Treatment of snoring and obstructive sleep apnea with a dental orthosis. *Chest* 1991;99:1378-85.
- Clark GT, Arand D, Chung E, Tongg D. Effect of anterior mandibular positioning on obstructive sleep apnea. *Am Rev Respir Dis* 1993;147:624-9.
- Knudson RC, Meyer JB Jr. Managing obstructive sleep apnea. *JADA* 1993;124:75-8.
- Eveloff SE, Rosenberg CL, Carlisle CC, Millman RP. Efficacy of a Herbst mandibular advancement device in obstructive sleep apnea. *Am J Respir Crit Care Med* 1994;149:905-9.
- O'Sullivan RA, Hillman DR, Mateljan R, Pantin C, Finucane KE. Mandibular advancement splint: An appliance to treat snoring and obstructive sleep apnea. *Am J Respir Crit Care Med* 1995;151:194-8.
- Ferguson KA, Ono T, Lowe AA, Keenan SP, Fleetham JA. A randomized crossover study of an oral appliance vs nasal-continuous positive airway pressure in the treatment of mild-moderate obstructive sleep apnea. *Chest* 1996;109:1269-75.

- Menn SJ, Loube DI, Morgan TD, Mitler MM, Berger JS, Erman MK. The mandibular repositioning device: role in the treatment of obstructive sleep apnea. *Sleep* 1996;19:794-800.
- Bernhold M, Bondemark L. A magnetic appliance for treatment of snoring patients with and without obstructive sleep apnea. *Am J Orthod Dentofac Orthop* 1998;113:144-55.
- Marklund M, Franklin KA, Sahlin C, Lundgren R. The effect of a mandibular advancement device on apneas and sleep in patients with obstructive sleep apnea. *Chest* 1998;113:707-13.
- Liu Y, Zeng X, Fu M, Huang X, Lowe AA. Effects of a mandibular repositioner on obstructive sleep apnea. *Am J Orthod Dentofac Orthop* 2000;118:248-56.
- Lowe AA, Sjöholm TT, Ryan CF, Fleetham JA, Ferguson KA, Remmers JE. Treatment, airway and compliance effects of a titratable oral appliance. *Sleep* 2000;23:S172-8.
- Petitjean T, Chammas N, Langevin B, Philit F, Robert D. Principles of mandibular advancement device applied to the therapeutic of snoring and sleep apnea syndrome. *Sleep* 2000;23:S166-71.
- Marklund M, Sahlin C, Stenlund H, Persson M, Franklin KA. Mandibular advancement device in patients with obstructive sleep apnea. *Chest* 2001;120:162-9.
- Mehta A, Qian J, Petocz P, Darendeliler MA, Cistulli PA. A randomized, controlled study of a mandibular advancement splint for obstructive sleep apnea. *Am J Respir Crit Care Med* 2001;163:1457-61.
- Cobo J, Canut JA, Carlos F, Vijande M, LLamas JM. Changes in the upper airway of patients who wear a modified functional appliance to treat obstructive sleep apnea. *Int J Adult Orthod Orthognath Surg* 1995;10:53-7.
- Ferguson KA, Love LL, Ryan CF. Effect of mandibular and tongue protrusion on upper airway size during wakefulness. *Am J Respir Crit Care Med* 1997;155:1748-54.
- Tsuiki S, Hiyama S, Ono T, Imamura N, Ishiwata Y, Kuroda T, Lowe AA. Effects of a titratable oral appliance on supine airway size in awake non-apneic individuals. *Sleep* 2001;24:554-60.
- Hiyama S, Ono T, Ishiwata Y, Kuroda T. Supine cephalometric study on sleep-related changes in upper-airway structures in normal subjects. *Sleep* 2000;23:783-90.
- Hiyama S, Ono T, Ishiwata Y, Kuroda T. Changes in mandibular position and upper-airway dimension by wearing cervical headgear during sleep. *Am J Orthod Dentofac Orthop* 2001;120:160-8.
- Tangel DJ, Mezzanotte WS, Sandberg EJ, White DP. Influences of NREM sleep on the activity of tonic vs. inspiratory phasic muscles in normal men. *J Appl Physiol* 1992;73:1058-66.
- Sauerland EK, Harper RM. The human tongue during sleep: electromyographic activity of the genioglossus muscle. *Exp Neurol* 1976;51:160-70.
- Wiegand DA, Latz B, Zwillich CW, Wiegand L. Geniohyoid muscle activity in normal men during wakefulness and sleep. *J Appl Physiol* 1990;69:1262-9.
- Isono S, Tanaka A, Sho Y, Konno A, Nishino T. Advancement of the mandible improves velopharyngeal airway patency. *J Appl Physiol* 1995;79:2132-8.
- Suratt PM, Dee P, Atkinson RL, Armstrong P, Wilhoit SC. Fluoroscopic and computed tomographic features of the pharyngeal airway in obstructive sleep apnea. *Am Rev Respir Dis* 1983;127:487-92.
- Morrison DL, Launois SH, Isono S, Feroah TR, Whitelaw WA, Remmers JE. Pharyngeal narrowing and closing pressure in patients with obstructive sleep apnea. *Am Rev Respir Dis* 1993;148:606-11.
- Trudo FJ, Gefter WB, Welch KC, Gupta KB, Maislin G, Schwab RJ. State-related changes in upper airway caliber and surrounding soft-tissue structures in normal subjects. *Am J Respir Crit Care Med* 1998;158:1259-70.
- Van de Graaff WB, Gottfried SB, Mitra J, Van Lunteren E, Cherniack NS, Strohl KP. Respiratory function of hyoid muscles and hyoid arch. *J Appl Physiol: Respirat Environ Exercise Physiol* 1984;57:197-204.
- van Lunteren E, Haxhiu MA, Cherniack NS. Relation between upper airway volume and hyoid muscle length. *J Appl Physiol* 1987;63:1443-9.
- Takagi Y, Gamble JW, Proffit WR, Christiansen RL. Postural change of the hyoid bone following osteotomy of the mandible. *Oral Surg Oral Med Oral Pathol* 1967;23:688-92.
- Nakagawa F, Ono T, Ishiwata Y, Kuroda T. Morphologic changes in the upper airway structure following surgical correction of mandibular prognathism. *Int J Adult Orthod Orthognath Surg* 1998;13:299-306.
- Prachartam N, Hans MG, Strohl KP, Redline S. Upright and supine cephalometric evaluation of obstructive sleep apnea syndrome and snoring subjects. *Angle Orthod* 1994;64:63-74.
- Lowe AA, Ono T, Ferguson KA, Pae EK, Ryan CF, Fleetham JA. Cephalometric comparisons of craniofacial and upper airway structure by skeletal subtype and gender in patients with obstructive sleep apnea. *Am J Orthod Dentofac Orthop* 1996;110:653-64.
- Brown IB, McClean PA, Boucher R, Zamel N, Hoffstein V. Changes in pharyngeal cross-sectional area with posture and application of continuous positive airway pressure in patients with obstructive sleep apnea. *Am Rev Respir Dis* 1987;136:628-32.
- Miyamoto K, Ozbek MM, Lowe AA, Fleetham JA. Effect of body position on tongue posture in awake patients with obstructive sleep apnoea. *Thorax* 1997;52:255-9.
- Cartwright RD, Lloyd S, Lilie J, Kravitz H. Sleep position training as treatment for sleep apnea syndrome: a preliminary study. *Sleep* 1985;8:87-94.
- Chase MH, McGinty DJ, Sterman MB. Cyclic variation in the amplitude of a brain stem reflex during sleep and wakefulness. *Experientia* 1968;24:47-8.
- Miyamoto K, Ozbek MM, Lowe AA, et al. Mandibular posture during sleep in healthy adults. *Arch Oral Biol* 1998;43:269-75.
- Britton PD. Effect of respiration on nasopharyngeal radiographs when assessing adenoidal enlargement. *J Laryngol Otol* 1989;103:71-3.
- Schwab RJ, Gefter WB, Pack AI, Hoffman EA. Dynamic imaging of the upper airway during respiration in normal subject. *J Appl Physiol* 1993;74:1504-14.
- Nakagawa F, Ono T, Ishiwata Y, Kuroda T. The morphological changes in the oropharynx in association with the respiratory phase. *Jpn Orthod Soc* 1996;55:337-44.