**Original Article**

# Exploring the Widespread Effectiveness of Maxillomandibular Advancement

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Keywords : maxillomandibular advancement, computed fluid dynamics, obstructive sleep apnea, nasal obstruction, pharyngeal airway

Abstract :

**Objectives:** Maxillomandibular advancement (MMA) for obstructive sleep apnea (OSA) is considered the useful treatment; however, its wide effectiveness is unclear. Thus, this study aimed to explore factors affecting the efficacy of MMA for OSA using a 3-D morphological and computed fluid dynamics (CFD) analysis of the upper airway (UA).

**Design:** Retrospective study

**Settings and participants:** Twenty consecutive patients (six women, mean age 34.2 ± 12.4 years) who underwent MMA because of persistent OSA at our center.

**Main outcome measures:** Cone-beam computed tomography images were captured before and after MMA. We assessed the maxilla and mandibular positions, cross-sectional areas of the nasal airway (NA) and pharyngeal airway (PA), and PA space (PAS). The negative pressure of the PA, NA, and UA were measured at inspiration using CFD. We performed paired t-tests and Wilcoxon signed-rank test to compare values before and after MMA. The relationship between the airway size and pressure was evaluated using Spearman correlation coefficients and a non-linear regression analysis.

**Results:** PAS significantly expanded from 6.5 ± 3.4 mm to 12.2 ± 3.8 mm. NA obstruction significantly improved from -312.6 ± 265.0 Pa to -76.2 ± 129.0 Pa. Moreover, the patients were divided into four types according to the PAS size and presence of NA obstruction, namely narrow PAS with NA obstruction, narrow PAS, NA obstruction, and wide PAS and without NA obstruction.

**Conclusions:** We identified variations in the OSA types. However, MMA substantially improved NA obstruction and PA expansion. Thus, we considered that MMA for OSA was effective for various types.

## Introduction

Obstructive sleep apnea (OSA) results from the obstruction of the pharyngeal airway (PA) during sleep. Maxillomandibular advancement (MMA) expands the PA as the surgical treatment for adult OSA; it is considered the useful treatment (success rate 86.0%, cure rate 43.2%)[1]. However, the factors mediating its widespread effectiveness are unclear. Despite several MMA studies[2-7], the association between the form and ventilation condition of the PA is not apparent. Therefore, researchers failed to elucidate the mechanism underlying MMA-mediated improvement of OSA symptoms. Furthermore, OSA in adults is displayed both in

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narrow PAS (≤ 5–6 mm) and wide PAS (approximately 9–11 mm)[2, 4, 7]. In addition, MMA expanded the PA in both cases and demonstrated improvements.

However, the mechanism underlying MMA-mediated OSA improvement by greater expansion of the PA is unclear in case of a wide and uneventful airway. As this reason, Lefort I maxilla osteotomy study that the cases were without OSA cases improved the nasal airway (NA) ventilation obstruction[8-11]. Therefore, MMA is expected to improve NA ventilation obstruction following Lefort I surgery of the maxilla. Thus, NA improvement by MMA possibly improved OSA symptoms. However, the process by which the effect of MMA on the NA and PA influences OSA symptom improvement is unclear. This warrants examining the entire upper airway (UA), which includes both NA and PA. However, researchers have not yet established a method for comprehensively evaluating the UA of both the NA and PA. They could not determine a mechanism of OSA improvement without comprehensively evaluating the entire UA. Recently, clinicians began using computed fluid dynamics (CFD) for evaluating the ventilation condition of the UA[12, 13]. It can simultaneously evaluate ventilation conditions of the entire UA and other parts. Thus, we aimed to assess the entire UA, including the NA and PA, using CFD to determine comprehensively the effect of MMA from the airway form and ventilation condition. Moreover, we intended to explore the factors affecting the widespread effectiveness of MMA.

## Materials and Methods

### Institutional Review Board

All study participants provided informed consent, and this study was approved by the Institutional Review Board of the ethics committees of the universities (180073 [657] Epi-ver.9 and 4018-1). It complied with the 1964 tenets of the Declaration of Helsinki and its subsequent amendments. Informed consent was obtained from all participating patients.

### Patients

Twenty consecutive patients (six women, mean age 34.2 ± 12.4 years, BMI 25.0 ± 4.8 kg/m$^2$, respiratory disturbance index [RDI][14]) = 26.2 ± 20.0) who underwent MMA owing to persistent OSA at our center were included in this retrospective study. We included adults aged between 16 years and 55 years who underwent preoperative polysomnography (PSG) to measure the RDI, and pre- and post-cone-beam computed tomography (CBCT) scan whose data had a craniocervical inclination of 95-105 degree[15], without swallowing, and pre- and post-Epworth sleepiness scale (ESS)[16] was evaluated. We performed a morphological analysis of cephalometric images from the CBCT data[17]. Traditional cephalometric measurements[17] were used to determine the positions of the maxilla and mandible. The horizontal (x) and vertical (y) positions of the selected landmarks were based on the coordinates relative to a reference plane parallel to the Frankfort horizontal plane and passing through the sella, which acted as the origin (Figure 1A).

### Cross-sectional area of the NA

A 3-D coordinate system and 3-D images were constructed using a medical image analyzing system (ImagnosisVE®, Imagnosis, Kobe, Japan) based on CBCT data. Before surgery, the cross-sectional area of the anterior NA ($CSA_{NAa}$) was defined as that lying in the frontal plane through the anterior nasal spine (ANS) (Figure 1B and 1C). Contrarily, the cross-sectional area of the posterior NA ($CSA_{NAp}$) was defined as that lying in the frontal plane through the palatal root tip of maxillary first molar (Figure 1B and 1D)[18]. Furthermore, after surgery, because ANS was reduced by spina osteotomy, it was set the datum-point which corresponded to ANS for measurement of $CSA_{NAa}$ in reference to an upper incisor cutting edge. Following surgery, the $CSA_{NAp}$ was measured using a method similar to that during pre-surgery. PA cross-sectional measurements included the $CSA_{PA}$ and PA space (PAS; the depth of anteroposterior direction) parallel to the palatal plane at the narrowest part of the airway (Figure 1E)[17].

### CFD

To evaluate the ventilation conditions of the UA (from the nare to epiglottis)[19], including the NA (from the nare to choana) and PA (from the palatal plane to epiglottis)[17], 3-D images were reconstructed from the CBCT data[17, 19]. Using a mesh-morphing software (DEP Mesh Works/Morpher®, IDAJ, Kobe, Japan), the 3-D model was converted to a smoothed model without losing the patient-specific character of the airway shape. We performed CFD to evaluate the ventilation condition of the airways[19]. The constructed 3-D smooth models were exported to the fluid-dynamic software (PHOENICS®, CHAM-Japan, Tokyo, Japan) in stereolithographic format. The ventilation condition estimated the NA and UA pressure using the 3-D UA model (Fig 1F left) and the PA pressure using the PA model before and after MMA (Fig 1F right). The NA resistance value to turn nasal breathing into mouth breathing was 0.3 Pa/mL/s[18]. We used this value to define airway obstruction by the CFD analysis. However, the airway resistance values depend on the air threshold and the method of mesh-morphing employed while constructing the airway model. Therefore, we regulated the construction of the airway model such that the NA resistance value obtained by the CFD analysis corresponded to the value derived from rhinomanometry[19].

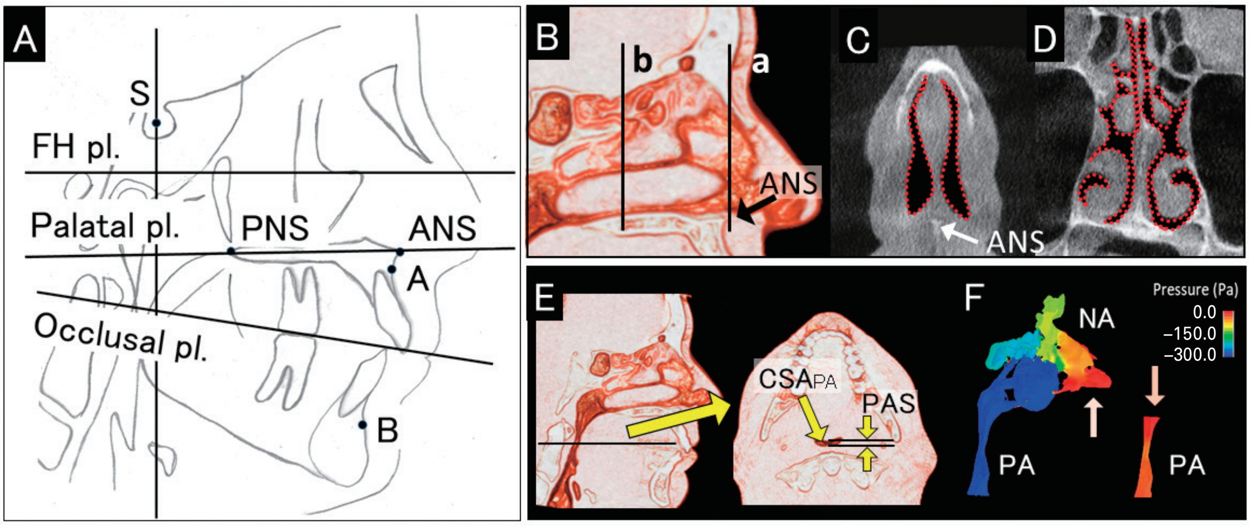


Fig. 1 Measurement of the morphological parameters and ventilation conditions

A: Anteroposterior and vertical cephalometric landmark positions measured parallel and perpendicular to the FH plane S, Sella; A, A-point; B, B-point; ANS, anterior nasal spine; PNS, posterior nasal spne; FH pl., Frankfurt horizontal plane; Palatal pl., palatal plane; Occlusal pl., Occlusal plane.

B: Definition of the cross-sectional area of the nasal airway ($CSA_{NA}$) a, measurement site of the anterior $CSA_{NA}$; and b, measurement site of the posterior $CSA_{NA}$.

C: $CSA_{NAa}$, anterior $CSA_{NA}$ at point a.

D: $CSA_{NAp}$, posterior $CSA_{NA}$ at point p.

E: Landmarks and planes for the axial airway section; a plane parallel to the palatal plane passing through the narrowest point on the soft palate. Cross-sectional areas of the pharyngeal airway ($CSA_{PA}$). PAS, Pharyngeal airway space, anteroposterior depth.

F: An evaluation of the nasal airway (NA), pharyngeal airway (PA), and upper airway (UA) of the ventilation condition (pressure) using computational fluid dynamics.

We collected sleep data from all patients who underwent preoperative and postoperative CBCT scan and ESS evaluation. They underwent PSG; we analyzed the RDI and lowest oxygen saturation.

## Statistical analysis

Paired t-tests were performed to compare the morphological parameters before and after MMA. We conducted the Wilcoxon signed-rank test to compare ventilation conditions before and after MMA. Spearman correlation coefficients were calculated to evaluate the relationships between morphological measurements and ventilation conditions of both pre- and post-MMA data. The relationship between $CSA_{PA}$ and PA pressure was evaluated by non-liner regression analysis. For all tests, $P < 0.05$ was considered statistically significant. We performed a power analysis to calculate the $\beta$ error ($1 - \beta$ error $= 0.80$, $\alpha = 0.05$, two-tailed test). The results confirmed the adequacy of the sample size. For the intra- and inter-examiner reliability, we used a random number generator to select 10 participants. These measurements were repeated 1 week after the initial measurements. Both intra- and inter-examiner reliability tests exhibited high correlation ranging from 0.974 to 0.985 for all measures.

## Results

Twenty patients were divided into four types according to their UA features using pre-PAS and NA pressure (Table 1).

**Type I:** six patients, narrow PAS (≤ 6 mm)[1] and NA obstruction (Nasal-obst; < -150 Pa, corresponding to 0.3 Pa/ml/sec)[18],

**Type II:** four patients, narrow PAS without NA obstruction (> -150 Pa),

**Type III:** six patients, without narrow PAS (> 6 mm) and NA obstruction (Nasal-obst; < -150 Pa,),

**Type IV:** three patients, neither narrow PAS nor NA obstruction.

Table 1 Individual data for age, sex, BMI, and upper airway feature (pharyngeal airway space, nasal, pharyngeal, and upper airway ventilation condition), and ESS

| No | age (year) | sex | BMI (Kg/m2) | Before PAS (mm) | After PAS (mm) | Before NA Pressure (Pa) | After NA Pressure (Pa) | Before PA Pressure (Pa) | After PA Pressure (Pa) | Before UA Pressure (Pa) | After UA Pressure (Pa) | Before ESS | After ESS | Uppper airway Type |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 48 | f | 22.2 | 2.1 | 8.1 | −830.1 | −19.3 | −39.9 | −6.7 | −870.0 | −26.0 | − | − | narrow PAS + NA-obst |
| 2 | 41 | m | 28.6 | 4.3 | 8.0 | −712.1 | −8.8 | −42.4 | −11.3 | −754.5 | −20.1 | 16 | 7 | narrow PAS + NA-obst |
| 3 | 31 | m | 24.4 | 5.0 | 7.0 | −689.8 | −189.7 | −43.1 | −25.3 | −732.9 | −215.0 | 11 | 5 | narrow PAS + NA-obst |
| 4 | 55 | m | 29.3 | 4.9 | 11.1 | −457.2 | −4.4 | −40.0 | −2.1 | −497.2 | −6.5 | 12 | 6 | narrow PAS + NA-obst |
| 5 | 22 | f | 21.7 | 5.4 | 8.3 | −358.1 | −17.0 | −11.4 | −13.5 | −369.5 | −30.5 | 13 | 5 | narrow PAS + NA-obst |
| 6 | 18 | m | 21.0 | 5.5 | 9.9 | −197.9 | −145.0 | −17.4 | −11.7 | −215.3 | −156.7 | 13 | 12 | narrow PAS + NA-obst |
| 7 | 17 | m | 20.6 | 3.3 | 11.6 | −140.1 | −22.8 | −38.0 | −4.4 | −178.1 | −27.3 | 12 | 4 | narrow PAS |
| 8 | 26 | m | 27.6 | 1.4 | 8.3 | −101.1 | −98.0 | −139.0 | −4.0 | −240.1 | −102.0 | 19 | 6 | narrow PAS |
| 9 | 43 | m | 37.3 | 3.2 | 13.8 | −98.5 | −49.8 | −93.2 | −5.3 | −191.7 | −55.1 | 16 | 5 | narrow PAS |
| 10 | 34 | f | 26.7 | 4.4 | 9.7 | −81.2 | −29.9 | −24.3 | −10.3 | −105.5 | −40.3 | 16 | 6 | narrow PAS |
| 11 | 36 | f | 18.3 | 7.8 | 13.8 | −781.2 | −17.2 | −5.4 | −2.8 | −786.6 | −20.0 | − | − | NA-obst |
| 12 | 42 | m | 32.5 | 8.5 | 15.5 | −521.4 | −583.7 | −20.6 | −11.9 | −542.0 | −595.6 | 14 | 10 | NA-obst |
| 13 | 52 | m | 24.4 | 11.0 | 14.5 | −337.1 | −53.8 | −4.5 | −1.4 | −341.6 | −55.2 | 15 | 9 | NA-obst |
| 14 | 25 | m | 25.5 | 6.8 | 13.1 | −279.2 | −47.6 | −12.7 | −4.5 | −291.9 | −52.1 | 12 | 7 | NA-obst |
| 15 | 37 | m | 27.6 | 8.1 | 11.4 | −211.7 | −103.5 | −19.3 | −9.2 | −231.0 | −112.7 | 12 | 10 | NA-obst |
| 16 | 52 | f | 19.3 | 6.2 | 14.3 | −201.2 | −44.4 | −18.9 | −6.1 | −220.1 | −50.5 | 13 | 4 | NA-obst |
| 17 | 18 | m | 22.0 | 10.5 | 13.3 | −178.2 | −19.2 | −26.0 | −0.9 | −204.2 | −20.1 | 15 | 5 | NA-obst |
| 18 | 36 | m | 27.4 | 8.9 | 19.0 | −51.3 | −35.7 | −3.2 | −1.5 | −54.5 | −37.2 | 18 | 8 | No-Feature |
| 19 | 16 | f | 22.6 | 15.8 | 22.2 | −21.2 | −11.2 | −4.9 | −2.8 | −26.1 | −14.0 | 14 | 3 | No-Feature |
| 20 | 34 | m | 20.1 | 7.4 | 11.6 | −3.2 | −21.9 | −5.8 | −3.5 | −9.0 | −25.4 | 13 | 4 | No-Feature |
| mean ±SD | 34.2 ±12.4 | | 25.0 ±4.8 | 6.5 ±3.4 | 12.2 ±3.8* | −312.6 ±265.0 | −76.2 ±129.0* | −30.5 ±33.1 | −7.0 ±5.9* | −343.1 ±265.4 | −83.1 ±131.6* | 14.1 ±2.2 | 6.4 ±2.5* | |

Before; before Maxillomandibular advancement, After; after Maxillomandibular advancement, PAS; pharyngeal airway space, NA; nasal airway, PA; pharyngeal airway, UA; upper airway, ESS; epworth Sleepness Scale evaluation, narrow PAS; PAS < 6 mm, NA-obst; nasal airway presure < −150 Pa, No-feature; neither narrow PAS nor NA-obst, * p < 0.01 Before vs After.

Table 2 morphological and ESS analysis

| | Before MMA | | After MMA | | Change | | |
|---|---|---|---|---|---|---|---|
| | mean | SD | mean | SD | mean | SD | P |
| Ax (mm) | 67.8 | 5.2 | 71.8 | 5.6 | 3.9 | 1.8 | < 0.001 |
| Ay (mm) | 30.0 | 4.0 | 32.4 | 3.3 | 2.4 | 2.6 | < 0.001 |
| Bx (mm) | 60.5 | 14.2 | 67.7 | 15.4 | 7.3 | 3.1 | < 0.001 |
| By (mm) | 63.2 | 13.8 | 65.6 | 14.3 | 2.6 | 2.2 | < 0.001 |
| ANSx (mm) | 74.7 | 4.1 | 78.9 | 4.3 | 4.2 | 2.5 | < 0.001 |
| ANSy (mm) | 22.7 | 3.1 | 21.4 | 3.3 | −1.3 | 2.5 | 0.035 |
| PNSx (mm) | 20.3 | 3.8 | 25.1 | 4.4 | 4.8 | 3.5 | < 0.001 |
| PNSy (mm) | 23.6 | 4.1 | 26.5 | 4.0 | 2.9 | 2.0 | < 0.001 |
| Palatal pl. (degree) | 90.0 | 4.5 | 85.5 | 5.1 | −4.5 | 4.1 | < 0.001 |
| Occlusal pl. (degree) | 92.6 | 4.3 | 88.3 | 3.8 | −4.4 | 4.5 | < 0.001 |
| $CSA_{PA}$ ($mm^2$) | 160.7 | 127.3 | 354.5 | 142.5 | 191.1 | 106.8 | < 0.001 |
| $CSA_{NAa}$ ($mm^2$) | 213.3 | 53.3 | 243.3 | 43.8 | 30.0 | 20.9 | < 0.001 |
| $CSA_{NAp}$ ($mm^2$) | 317.3 | 80.6 | 416.8 | 108.0 | 99.5 | 91.2 | < 0.001 |
| ESS | 14.1 | 2.2 | 6.4 | 2.5 | −7.7 | 3.2 | < 0.001 |

$CSA_{PA}$: cross-sectional area of pharyngeal airway, $CSA_{NAa}$: cross-sectional area of anterior nasal airway, $CSA_{NAp}$: cross-sectional area of psterior nasal airway, ESS: epworth sleepiness scale.

## Morphological analysis

The maxilla advanced 3.9 ± 1.8 mm at the anterior nasal spine (Table 2). Vertically, the ANS was moved upward by 1.3 ± 2.5 mm and the posterior nasal spine moved downward by 2.9 ± 2.0 mm, thus demonstrating counterclockwise rotation of the maxilla (-4.5 ± 4.1°). The mandible advanced by 8.3 ± 3.2 mm at the B-point. Vertically, the B-point moved downward by 2.6 ± 2.3 mm. An airway analysis revealed that the PAS significantly increased from 6.5 ± 3.4 mm to 12.2 ± 3.8 mm. Furthermore, the $CSA_{PA}$ significantly increased

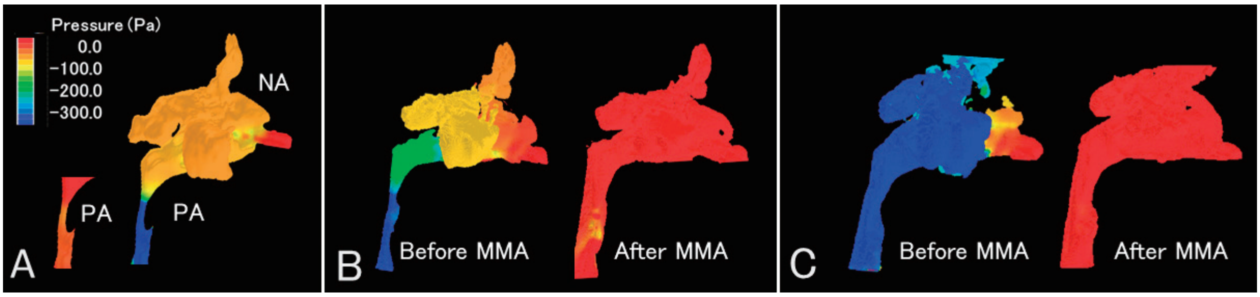


Fig. 2 Effects of maxillomandibular advancement (MMA) by the computational fluid dynamics analysis and its impact on the pharyngeal airway (PA) and nasal airway (NA) obstruction.
A: Effects on the PA of NA obstruction. During NA obstruction, the negative pressure of the PA part (Right) is stronger than negative pressure only for PA (Left). It shows that effect on PA of the NA obstruction.
B: Obstructive sleep apnea (OSA) case with a narrow PA. Before treatment (left), PA is narrow; strong negative pressure observed in the PA, besides occlusion. Following treatment (right), the PA has expanded; the negative pressure has relieved and the obstruction of the PA has dissolved. MMA has improved OSA symptoms.
C: OSA case with NA obstruction. Before treatment (left), the PA is not narrow; however, strong negative pressure occurs in the PA because of obstructed NA ventilation. Eventually, the PA has collapsed. Following treatment (right), MMA has improved obstructed NA ventilation and relieved the negative pressure of the PA. Eventually, the OSA has improved.

from 160.7 ± 127.3 $mm^2$ to 354.5 ± 142.5 $mm^2$. $CSA_{NAa}$ and $CSA_{NAp}$ significantly increased from 213.3 ± 53.3 $mm^2$ to 243.3 ± 43.8 $mm^2$ and 317.3 ± 80.6 $mm^2$ to 416.8 ± 108.6 $mm^2$, respectively.

### CFD analysis

The NA pressure significantly reduced from -312.6 ± 265.0 Pa to -76.2 ± 129.0 Pa; the PA pressure significantly reduced from -30.5 ± 33.1 Pa to -7.0 ± 5.9 Pa. The total airway pressure significantly reduced from -343.1 ± 265.4 Pa to -83.1 ± 131.6 Pa (Table 1).

Regarding the ventilation condition difference between UA model and PA model, the pressure value of the PA part of the UA model was greater than that of the PA model (Table 1 and Figure 2A).

### Correlation analysis

The NA pressure was not significantly correlated with the $CSA_{NAa}$ (rs = 0.289, P = 0.07); however, it was positively correlated with the $CSA_{NAp}$ (rs = 0.559, $P < 0.001$). The PA pressure was positively correlated with the PAS and $CSA_{PA}$ (rs = 0.791, $P < 0.001$; rs = 0.813, $P < 0.001$, respectively). The non-liner regression equation depicts the distributions of the PAS and PA pressure in this study (Figure 3). The relationship between the PAS and pressure was represented by a fitted curve that was inversely proportional to the square of the PAS between the pre- and postoperative data ($R^2$ = 0.676, $P < 0.001$). The pharyngeal airway pressure markedly increased for a PAS ≤ 5 mm. A PAS of 3 mm revealed that the corresponding pressure was approximately -150 Pa. The ESS was significant correlated with the PAS (rs = 0.560, $P < 0.001$), $CSA_{PA}$ (rs = 0.556, $P < 0.001$), $CSA_{NAp}$ (rs = 0.399, $P < 0.016$), NA pressure (rs = 0.513, $P < 0.001$), PA pressure (rs = 0.519, $P < 0.001$), and total airway pressure (rs = 0.574, $P < 0.001$).

## Discussion

This study explored the factors affecting the effectiveness of MMA based on a morphological 3-D analysis and fluid analysis of the UA. Effectiveness of MMA was shown that not only expanded the PA but also improved NA obstruction.

Following OSA surgical treatment, OSA symptoms improved not by the only expansion of the PA[1, 3, 4, 20]. However, there are few reports have considered differences in the form of PA and UA ventilation condition in relation to CSA.

### Effects of MMA

Regarding the expansion of the PA by MMA, the impaction of anterior part of maxilla was performed with the rotation center at the maxillary buttress and an extruded maxillary posterior region. Thus, the occlusal plane was rotated counterclockwise. The maxilla and mandible were shifted to the forward region by more than half[21, 22] of the conventional degree[20]. Furthermore, the PA of 5 mm was expanded similar to that in previous studies[21, 22]. We confirmed the expansion effect of the PA by counterclockwise MMA.

The PAS and $CSA_{PA}$ revealed a regression equation of the

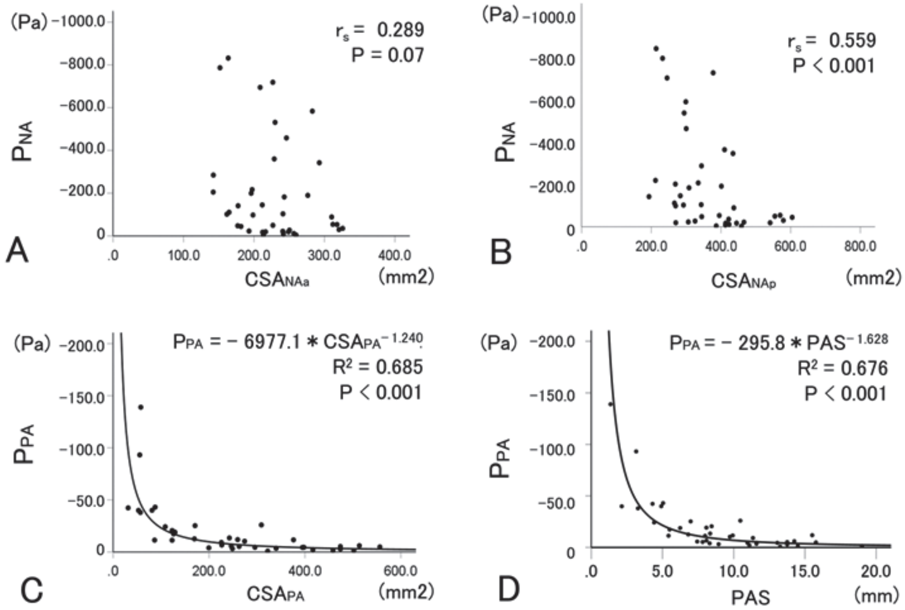


Fig. 3 Relationships between the cross-sectional airway area and airway pressure.
A: Relationships between the cross-sectional area of the anterior nasal airway ($CSA_{NAa}$) and nasal airway pressure ($P_{NA}$). The relationships are insignificant and the pressure value is distributed widely.
B: Relationships between the cross-sectional area of the posterior nasal airway ($CSA_{NAp}$) and $P_{NA}$. The relationships are marginally significant (rs = 0.599 P < 0.001). However, the pressure value is distributed widely.
C: Relationships between the cross-sectional area of the pharyngeal airway ($CSA_{PA}$) and pharyngeal airway pressure ($P_{PA}$). The non-linear regression equation describing the relationship between the $CSA_{PA}$ and $P_{PA}$ represent a power function. The relationship between $CSA_{PA}$ and $P_{PA}$ is depicted by the fitted curve, which is an inversely proportional curve between the pre- and postoperative data.
D: Relationships between the pharyngeal airway space (PAS) and $P_{PA}$. The relationship between the PAS and PPA is similar to that between the $CSA_{PA}$ and $P_{PA}$.

pressure of the PA and a similar tendency (Figure 3C and 3D). Therefore, we considered the PAS appropriate for a morphological index to depict the ventilation condition of the PA.

The PAS reached -150 Pa at approximately 2 mm from the regression line, which revealed the relations between the PAS and pharyngeal airway pressure (Figure 4A, black solid line) and suggested airway obstruction[18]. Several studies reported 6 mm of PAS in OSA[1]. Herein, a pressure value of -20 Pa corresponded to a PAS of 6 mm (Figure 4A, black solid line). However, it was relatively lower than -150 Pa[18] that causes ventilation obstruction. A conventional study reported that the PAS reduced to 2.8 mm during sleep in normal adults[23]. Therefore, we performed CBCT after awakening, in the sitting position, and while holding the breath at the end of the expiration; the PAS of 6 mm reduced to approximately 3 mm during sleep and in the supine position (Figure 4A, red solid curve line). Furthermore, the PA narrows under the influence of inspiratory negative pressure[24]. Therefore, a PAS of 6 mm at awakening substantially narrowed (≤ 2 mm) during sleep inspiration (Figure 4A, red dotted curve line). Moreover, NA obstruction is considered as a presence of strong pressure (≤ -150 Pa) that collapsed PA (Figure 4A, blue dotted curve line).

## A change in the NA following MMA

Until now, for the case without OSA, it is reported that after performing Lefort I surgery to make maxillary bone with forward movement, a cross section of isthmus of the NA expands it, and NA ventilation obstruction showed an improvement tendency[8-11]. In present study, a cross section of the NA expanded both the forward region and posterior region, in addition to obstructed NA ventilation.

We examined the PA pressure of both UA model (Figure 2A right) and PA model (Figure 2A left) using CFD. Nasal obstruction increased the negative pressure of the PA, besides increasing collapsibility. Previously, nasal obstruction caused OSA[1,25,26].

And improvement is expected in case of OSA-mediated

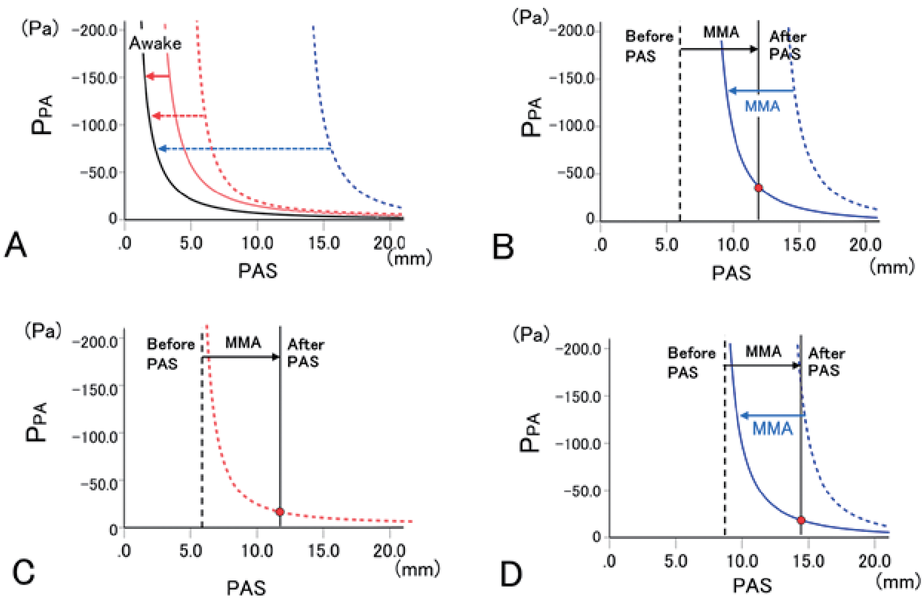


Fig. 4 Examples of fitted curve images of relationships between the pharyngeal airway space (PAS) and pressure.
A: Black solid curve line; fitted curve line relation between pharyngeal airway presuure and PAS at awake, sitting, and not inspiring position (present study result). Red solid curve line moves to the black solid curve line at sleep and supine position (red solid arrow). Red dotted curve line moves to the black solid curve line at sleep, in the supine position, and during inspiration without nasal airway (NA) obstruction (red dotted arrow). Blue dotted curve line moves to black solid curve line at sleep, in the supine position, and during inspiration with NA obstruction (blue dotted arrow).
B: Narrow PAS of 6 mm with nasal obstruction. Before maxillomandibular advancement (MMA), narrow PAS and large negative pressure is observed to collapse the pharyngeal airway (PA), besides supposedly occluded PA. After MMA, the PAS expanded to 12 mm (black solid arrow, the black dotted vertical straight line moved to the black solid vertical straight line) and the blue dotted curve line moved to the blue solid curve line at sleep, in the supine position, and during inspiration by improvement of NA obstruction (blue solid arrow), which displays reduced negative pressure without possible occlusion (red point), besides expected obstructive sleep apnea (OSA) improvement.
C: Narrow PAS of 6 mm without nasal obstruction. Before MMA, the narrow PAS corresponds to a large negative pressure, besides possibly occluded PA. After MMA, the PAS has expanded to 12 mm (black solid arrow, black dotted vertical straight line moved to black solid vertical straight line), which reveals reduced negative pressure without occlusion (red point), besides expected OSA improvement.
D: Wide PAS of 8 mm with nasal obstruction. Before MMA, large negative pressure collapses the PA, besides possible occlusion. After MMA, the PAS has expanded to 14 mm (black solid arrow, black dotted vertical straight line moved to black solid vertical straight line) and blue dotted curve line moves to blue solid curve line at sleep, supine position, and inspiration by improvement of NA obstruction (blue solid arrow), which reveals reduced negative pressure without occlusion (red point), besides expected OSA improvement.

nasal obstruction.

Garcia[27] investigated the NA cross section and relations of the ventilation condition in normal adults, which were predominantly influenced by the isthmus. However, the relation between ventilation conditions of $CSA_{NAp}$ was stronger than that of the $CSA_{NAa}$, which corresponded to the isthmus in this study; moreover, the effect was large. Owing to the complex relation between the NA cross section and ventilation condition, it could not display strong relations such as those with the PA (Figure 3). Thus, we could predict the ventilation of the PA from the PAS and $CSA_{PA}$ values; nonetheless, the grasp of the NA ventilation condition was difficult from CSA of the NA.

In a study of conventional OSA, size of the PA or the NA ventilation seem to be highly individual (Table 1). Thus, we performed classification based on the PA morphology and the ventilation condition of the NA. Eventually, adult patients with OSA could be classified to four categories, which demonstrated the collapse mechanism of the PA and improvement mechanisms by MMA.

Type I cases displayed nasal obstruction and a narrow PAS of 6 mm. The PAS narrowed during sleep at supine position[23]. Furthermore, the large negative inspiration pressure resulted in PA collapse[24]. MMA caused approximately 6 mm expansion of the PAS and an improvement of NA obstruction. Furthermore, the PA was considerably large and reduced negative inspiration pressure. It was improved to collapse of PA (Figure 4B).

Type II cases displayed a narrow PAS of 6 mm. The PAS narrowed during sleep, despite weak inspiration pressure at supine position, and eventually collapsed. MMA expanded the PAS to 12 mm. The PA was considerably large and prevented the collapse of PA during sleep (Figure 2B and Figure 4C).

The PAS was not narrow in type III cases; however, it displayed nasal obstruction. Despite wide PAS, large negative inspiration pressure resulted in collapsed PA. MMA improved the nasal obstruction. And it was improved to collapse of PA by improvement of nasal obstruction (Figure 2C and Figure 4D). However, CFD analysis of the entire UA revealed major negative pressure in the PA because of obstructed NA ventilation (Figure 2A).

Thus, the airway dilator muscle performed relaxation (low activity) during sleeping and the PA substantially narrowed, thereby leading to obstruction. Therefore, both narrow PA and NA obstruction were observed during PA obstruction at sleep inspiration. MMA demonstrated improvements in both NA obstruction and the expansion of the PA. In other words, MMA could extensively improve OSA symptoms.

Furthermore, were identified few cases with neither PAS nor NA ventilation obstruction (type IV). Thus, negative pressure required for PA collapse did not occur in these cases because of the absence of nasal obstruction.

However, PAS of a normal size were expected to collapse because of weak negative pressure during sleep. So, an airway surrounding tissue relaxes highly during sleep, or a histologically weak possibility was thought about. We considered that it was necessary to conduct further consideration in, future.

## Limitations

The study comprised a small sample size, thus warranting higher cases to inspect our findings and a comprehensive postoperative MMA-based prediction of the PA and NA in the future. However, several studies[2, 4, 7] demonstrated wide PAS in adults with OSA ranging from 1 mm to 10 mm, besides reports of nasal obstruction cases[26]. Thus, adults with OSA may manifest several variations in the UA, for example, narrow PA type, nasal obstruction type, narrow pharyngeal and nasal obstructed airway type, and other types. Furthermore, this is that not all the patients who were administered an ESS underwent subsequent polysomnography. This present study did not include objective measures of sleepiness and relied solely upon subjective and self-reported measurements. It may therefore prove beneficial to include other objective measures to further evaluation.

## Clinical implications

Our findings suggested the importance of analyzing the form and ventilation conditions of the UA, including both PA and NA during OSA treatment.

And it can be selectable the suitable treatment, and it was expected for a case that foreseeability improved.

## Conclusions

The OSA types varied in the present study. However, MMA exerted two effects, namely an improvement of the NA obstruction and an expansion of the PA. Thus, we considered that MMA for OSA was effective for various types.

## COI statement

All authors have no financial conflicts of interest to disclose concerning the study.

## Acknowledgments

This work was supported by KAKENHI from Japan Society for the Promotion of Science (No. 18K09860, 20K18766, 20K10230, 21K17189).

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