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Efficacy of Maxillomandibular Advancement Examined with Drug-Induced Sleep Endoscopy and Computational Fluid Dynamics Airflow Modeling

Stanley Yung-Chuan Liu, MD, DDS[1,2], Leh-Kiong Huon, MD[2,3,4], Tomonori Iwasaki, DDS, PhD[5], Audrey Yoon, DDS, MS[2], Robert Riley, MD, DDS[1], Nelson Powell, MD, DDS[1], Carlos Torre, MD[1], and Robson Capasso, MD[1]

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Abstract

Objectives. To use drug-induced sedation endoscopy (DISE) and computational fluid dynamics (CFD) modeling to study dynamic airway and airflow changes after maxillomandibular advancement (MMA), and how the changes correlate with surgical success based on polysomnography parameters.

Study Design. Retrospective cohort study.

Setting. University medical center.

Methods. DISE was rated with the VOTE (velum, oropharynx, tongue, epiglottis) classification, and CFD was used to model airflow velocity and negative pressure exerted on pharyngeal wall. Changes in VOTE score by site and CFD measurements were correlated with perioperative polysomnography outcomes of apnea-hypopnea index (AHI), apnea index (AI), oxygenation desaturation index (ODI), and lowest oxygen saturation.

Results. After MMA, 20 subjects (17 males, 3 females) with a mean age of 44 ± 12 years and body mass index of 27.4 ± 4.6 kg/m^2 showed mean decreases in AHI (53.6 ± 26.6 to 9.5 ± 7.4 events/h) and ODI (38.7 ± 30.3 to 8.1 ± 9.2 events/h; $P < .001$). Improvement in lateral pharyngeal wall collapse during DISE based on VOTE score correlated with the most decrease in AHI (60.0 ± 25.6 to 7.5 ± 3.4 events/h) and ODI (46.7 ± 29.8 to 5.3 ± 2 events/h; P = .002). CFD modeling showed significant positive Pearson correlations between reduction of retropalatal airflow velocity and AHI (r = 0.617, P = .04) and ODI (r = 0.773, P = .005).

Conclusion. AHI and ODI improvement after MMA is best correlated with (1) decreased retropalatal airflow velocity modeled by CFD and (2) increased lateral pharyngeal wall stability based on VOTE scoring from DISE.

Keywords

maxillomandibular advancement, obstructive sleep apnea, drug-induced sleep endoscopy, computational fluid dynamics, lateral pharyngeal wall collapse

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Of the surgical options available to patients with obstructive sleep apnea (OSA) who are intolerant of positive airway pressure therapy, maxillomandibular advancement (MMA) consistently demonstrates high rates of surgical success. Case series report a wide range of success rate, ranging from 56% to 100%.[1-8] The largest systematic review and meta-analysis of MMA to date with 627 subjects in 22 unique patient populations show pooled success and cure rates of 86% and 43.2%, respectively.[9] Vicini et al published the only randomized crossover trial comparing MMA with positive airway pressure, showing MMA as an effective alternative based on objective polysomnography

[1]Division of Sleep Surgery, Department of Otolaryngology Head and Neck Surgery, Stanford Hospital and Clinics, Stanford, California, USA
[2]School of Medicine, Stanford University, Stanford, California, USA
[3]Department of Otolaryngology, Head and Neck Surgery, Cathay General Hospital, Taipei, Taiwan
[4]School of Medicine, Fu Jen Catholic University, Taipei, Taiwan
[5]Field of Development Medicine, Health Research Course, Graduate School of Medicine and Dental Sciences, Kagoshima University, Kagoshima, Japan

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Corresponding Author:
Stanley Yung-Chuan Liu, MD, DDS, Assistant Professor of Otolaryngology, School of Medicine, Stanford University, 801 Welch Road, Stanford, CA 94305, USA.
Email: ycliu@stanford.edu

(PSG), subjective symptoms, and health-related quality-of-life measures.[10]

Most investigators attribute the efficacy of MMA to enlargement of upper airway space and decrease in pharyngeal collapsibility as a result of upper and lower jaw advancement. Common to published MMA studies is the use of static imaging or awake endoscopy for assessment of perioperative airway changes. The main weakness with these types of studies is not in the study design but in the methods used to study the disorder. The OSA airway does not manifest itself in a static or awake state. To better understand perioperative MMA airway changes and their correlations to surgical success, dynamic studies in sleep-like conditions are necessary.

Using drug-induced sedation endoscopy (DISE) to study pharyngeal wall behavior and computational fluid dynamics (CFD) to model airflow, we aimed to understand dynamic airway and airflow changes before and after MMA. Understanding mechanisms of MMA's efficacy using theoretical and real-time dynamic methods may improve surgical patient phenotyping and add insight to the development of less invasive procedures.

Methods

Study Design

This is a retrospective study conducted with a consecutive cohort of OSA subjects who underwent MMA with Stanford Sleep Surgery from July 2013 to December 2014. Subjects with and without previous intrapharyngeal surgery for OSA were included. Subjects were excluded if perioperative PSG or DISE data were missing or not yet obtained at time of study. Subjects were also excluded if presurgical orthodontic treatment was required for congenital or acquired dentofacial deformity. This included all subjects with maxillary transverse discrepancy with crossbite and class II or III jaw relationships. The surgical procedure and perioperative care follow the Powell-Riley protocol that evolved in our institution over the last 2 decades.[7,11-13] Postoperative sleep endoscopy was performed at the time of arch bar or piriform wire removal 5 to 7 weeks after MMA. Postoperative PSG was performed as close to 6 months after MMA as possible. Airway modeling based on CFD to study airflow and negative pressure along the pharyngeal wall was performed with perioperative computed tomograph (CT) scans. Preoperative CT scans were obtained for virtual surgical planning and usually within 1 month before surgery. Postoperative CT scans were performed on post-MMA day 1 to 2 for confirmation of proper osteotomy, fixation, and jaw position. This study was approved by the Institutional Review Board of Stanford University (protocol 29182, IRB 6208).

Polysomnography

Subjects underwent in-laboratory diagnostic PSG conducted and scored according to the standards of the American Academy of Sleep Medicine, including electroencephalography, electro-oculography, chin electromyography, and electrocardiography. Subjects had transcutaneous pulse oximetry, with respiratory effort recorded with inductance plethysmography. Apnea was measured by an oronasal thermistor and defined as a decrease of baseline airflow by $\geq$90% for at least 10 seconds. Hypopnea was measured by a nasal pressure cannula and defined as a partial obstructive event with decrease of airflow by $>$30% from baseline for at least 10 seconds. Hypopnea was also counted if there was oxygen desaturation $\geq$3%, with electroencephalogram-confirmed arousal.

Drug-Induced Sedation (Sleep) Endoscopy

DISE was uniformly performed in a dimmed and quieted operating room by experienced sleep surgeons. The nasal cavity is decongested with phenylephrine a half hour prior to the procedure. No local anesthetic spray was used. Drug-induced sedation was achieved with intravenous administration of dexmedetomidine via a target-controlled infusion system at a rate of 1.5 mcg/kg/h, after an initial loading dose of 1.5 mcg/kg is delivered over 10 minutes. Patients were not preoxygenated. Electrocardiography, blood pressure, and oxygen saturation were monitored during the procedure. Flexible nasopharyngoscope was used to sequentially observe the nasal cavity, nasopharynx, velum, oropharynx, tongue base, and epiglottis. Degree and pattern of collapse were recorded via the VOTE (velum, oropharynx, tongue, epiglottis) classification, which is a system that rates the pattern and grade of collapse at each of the aforementioned airway sites. At the level of the velum, pattern of collapse is classified as circumferential, anterior-posterior, or lateral to medial. At the oropharynx, it is lateral to medial. At the tongue, it is anterior to posterior. At the epiglottis, it is either anterior to posterior or lateral to medial. Grading of collapse is from 0 to 2, where 0 is no obstruction, 1 is between 25% and 75% airway obstruction, and 2 is $>$75% obstruction.[14]

CFD Airway Modeling of Flow and Pressure

Volume-rendering software (Intage Volume Editor; Cybernet, Tokyo, Japan) was used to generate 3-dimensional volume data of the upper airway. All CT scans were obtained at Stanford Hospital and Clinics, with subjects in supine position. Preoperative CT scans were obtained within 1 month before MMA, and postoperative scans were obtained 1 to 2 days after MMA. Subjects were asked to breathe regularly through the nose, with jaws closed in normal occlusion. Subjects whose scans were captured during active swallowing were excluded from CFD analysis. Constructed 3-dimensional images of the airway were exported to fluid dynamics software (Phoenics; CHAM-Japan, Tokyo, Japan) in stereolithographic format. Flow was assumed to consist of a Newtonian, homogenous, and incompressible fluid. Elliptic-staggered and continuity equations were used in the study. CFD of the airway was analyzed under the following conditions: (1) volume of airflow at velocity of 300 mL/s, (2) nonslippery wall surface, and (3) simulations repeated 1000 times for mean values. We conducted simulation of the nasal airway and the total upper airway during inspiration. Maximal negative pressure at the

Table 1. Patient Demographics, Perioperative Polysomnography Parameters, and Epworth Sleepiness Scale.[a]

	MMA, Mean ± SD		
	Before	After	*P* Value
Age, y	44 ± 12		
Body mass index, kg/m^2	27 ± 4.6	27.4 ± 4.6	.410
AHI, events/h	53.6 ± 26.6	9.5 ± 7.4	<.001
ODI, events/h	38.7 ± 30.3	8.1 ± 9.2	<.001
Lowest O_2 saturation, %	80.9 ± 8.9	94.1 ± 3.5	.001
Epworth Sleepiness Scale	17 ± 4.8	5.7 ± 2.7	<.001

Abbreviations: AHI, apnea-hypopnea index; MMA, maxillomandibular advancement; ODI, oxygen desaturation index.
[a]Patients, N = 20; 17 men, 3 women.

retropalatal and retroglossal regions was estimated. Retropalatal airway was defined from the level of the hard palate to inferior border of the uvula. The retroglossal airway extended from the inferior border of the uvula to the base of the epiglottis.

Statistical Analysis

Descriptive statistics were computed for all variables. Continuous variables were summarized through means and standard deviations and were compared with the Mann-Whitney-Wilcoxon test and the Student *t* test. The VOTE scores from DISE before and after MMA were assessed with the McNemar test. Pearson correlation was used for correlation between CFD parameters and PSG outcome. For all analyses, $P < .01$ was considered statistically significant given the small sample size, based on our power calculations.

Results

Demographic and perioperative PSG data of the subjects (17 male and 3 female) are summarized in **Table 1**. The age range is from 20 to 62 years. The mean maxillary advancement in our group is 7 ± 1.4 mm, with counterclockwise rotation of 10.2 ± 2.2 degrees. The center of rotation is based on the posterior nasal spine. Of the 20 subjects, 40% underwent MMA as the first surgical intervention for OSA, and the remainder had previously underwent tonsillectomy and adenoidectomy (35%), uvulopalatopharyngoplasty (15%), or combined palate and tongue surgery (10%). Two subjects had overjet >4 mm and could have been candidates for presurgical orthodontics, but they were comfortable with stable occlusion and elected to proceed with surgery only. They had dental arch length discrepancy but not facial skeletal dysmorphism.

After MMA, mean apnea-hypopnea index (AHI) was reduced from 53.6 ± 26.6 to 9.5 ± 7.4 events/h, mean apnea index from 15 ± 20.5 to 0.29 ± 0.2 events/h, and mean oxygenation desaturation index (ODI) from 38.7 ± 26.6 to 8.1 ± 9.2 events/h ($P < .001$). Mean lowest oxygen saturation increased from 80.9% ± 9% to 94.1% ± 4% (P = .001). Mean Epworth Sleepiness Scale score decreased from 17 ± 4.8 to 5.7 ± 2.7 ($P < .001$). Body mass index was not significantly different between baseline and time of PSG (approximately 6 months after surgery). Based on surgical success as determined with the criteria of Sher et al (postoperative AHI <20 events/h, with >50% reduction in the preoperative AHI),[15] success and cure rates of our cohort were 90% and 50%, respectively.

Perioperative patterns of airway collapse on DISE are listed in **Table 2**. All subjects exhibited multilevel collapse before MMA, with collapse of the lateral wall at the oropharynx as the most common site (95%), followed by tongue base collapse (85%) and concentric collapse at the velum (55%). Post-MMA change in the patterns of airway collapse was most frequently seen at the lateral wall of oropharynx, changing from 95% to 10% with partial collapse ($P < .001$). This was followed by change of concentric collapse at the velum, from 55% to 0% (P = .001). When examined by site of airway collapse, improvement in lateral pharyngeal wall collapse (VOTE score from 2 to 0) showed the most decrease in AHI (60.0 ± 25.6 to 7.5 ± 3.4 events/h; $P < .001$) and ODI (46.7 ± 29.8 to 5.3 ± 2 events/h; P = .002). This is followed by improvement in velum stability, with AHI decrease from 52.27 ± 28.6 to 8.24 ± 4.2 events/h (P = .015), and then tongue base stability, with AHI decrease from 43.51 ± 26.71 to 7.46 ± 3.73 events/h (P = .018).

Figures 1 and **2** show representative still images from DISE video of a 37-year-old man before and after MMA. He has a history of palatopharyngoplasty and a pre-MMA AHI of 50.7 events/h. His post-MMA AHI is 4.1 events/h (see supplemental videos at www.otojournal.org/supplemental, which show perioperative DISE of a 50-year-old woman with no previous soft tissue surgery before and after MMA; video 1, pre-MMA AHI of 43.4 events/h, with collapse of the velum, lateral pharyngeal wall, and tongue base; video 2, post-MMA AHI of 4.8 events/h, with improved stability at velum and lateral pharyngeal wall).

Table 3 shows the change in perioperative CFD parameters in our cohort. The most significant change in airflow velocity is at the retropalatal region, with a mean decrease from 19.3 ± 20.4 m/s to 6.6 ± 6.5 m/s (P = .003). Negative pressure along the airway also decreased significantly from –529 ± 788 Pa to –89 ± 43 Pa (P = .004).

Table 4 shows the Pearson correlation between change in CFD parameters and PSG outcome measures of AHI,

Table 2. Pattern of Upper Airway Collapse before and after MMA during DISE Rated by the VOTE Classification.[a]

	Before MMA			After MMA			
Level: Pattern Collapse	Partial, n	Complete, n	Obstruction, %	Partial, n	Complete, n	Obstruction, %	*P* Value
Velum							
A-P	4	4	40	2	0	10	.031
Lateral	3	2	25	0	0	0	.063
Concentric	2	9	55	0	0	0	.001
Oropharynx: lateral	2	17	95	2	0	10	.000
Tongue base: A-P	12	5	85	7	1	40	.004
Epiglottis							
A-P	2	2	20	1	1	10	.500
Lateral	0	2	10	1	0	5	1.000

Abbreviations: A-P, anterior-to-posterior pattern of airway collapse; DISE, drug-induced sedation endoscopy; MMA, maxillomandibular advancement; VOTE, velum, oropharynx, tongue, epiglottis.
[a]Patients, N = 20.

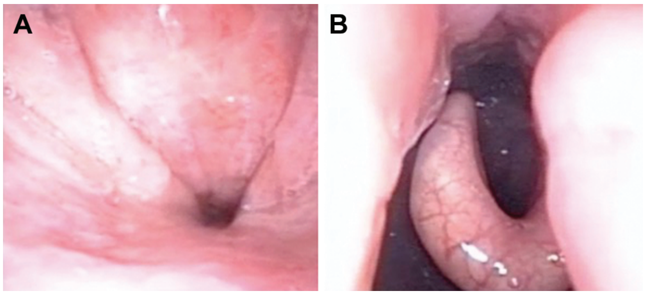

Figure 1. Pattern of airway collapse on drug-induced sleep endoscopy of a 37-year-old man before maxillomandibular advancement. A, Velum: concentric, complete collapse. B, Oropharynx: >75% lateral collapse.

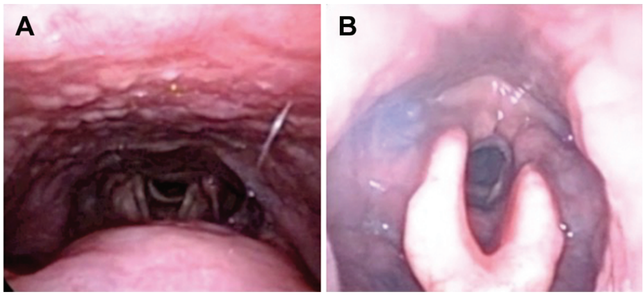

Figure 2. Pattern of airway collapse on drug-induced sleep endoscopy of a 37-year-old man after maxillomandibular advancement. A, Velum: no collapse. B, Oropharynx: no collapse.

ODI, and lowest oxygen saturation. Change in retropalatal air flow velocity correlates significantly with all 3 PSG outcomes. There is a significant negative correlation between ODI and retropalatal airway velocity (P = .002).

Discussion

We aimed to enhance understanding of the mechanism behind MMA's efficacy by examining dynamic perioperative airway and airflow changes using DISE and CFD modeling. Previous reports on MMA discuss the relationship of static measures based on 2- or 3-dimensional imaging and results of awake endoscopy to surgical success.[8,16-20] This MMA airway and airflow study offers new observations by concurrently using methods that more closely mimic the sleep state, and it examines beyond the static to the dynamic with modeling of airflow.

Using DISE, we found that MMA results in markedly increased stability of the lateral pharyngeal wall, followed by the velum and then the tongue base. This may explain its high success rate in patients who failed other types of surgical treatment. Soares et al reported that the presence of severe lateral pharyngeal wall collapse seen on preoperative DISE is associated with OSA surgical failure.[21] In that study, a comprehensive spectrum of surgical procedures was included, with the exception of MMA. Our group has also demonstrated a strong association between complete lateral pharyngeal wall collapse and increased OSA severity, particularly with objective oximetry measures.[22] Hence, for patients with severe lateral pharyngeal wall collapse on DISE, MMA is likely more effective than other types of surgical treatment due to stabilization of the lateral pharyngeal wall.

CFD for the OSA airway is a theoretical model for airflow and a sophisticated and noninvasive method to identify pharyngeal airflow characteristics.[23] As the modeling continues to improve, even non-MMA CFD models have shown feasibility in generating hypotheses for trials regarding anatomic manipulations in OSA.[24] In this study, we found that decrease of airflow velocity at the retropalatal airway after MMA is correlated with postoperative PSG outcome and is particularly strong with objective measures such as the oxygen desaturation index. Before surgery, greatest increased airflow velocity is seen at the retropalatal airway during inspiration and greatest negative pressure downstream (**Figure 3**). Postoperatively, negative pressure

Table 3. Perioperative Computational Fluid Dynamic Measurements.

Measurement	Before MMA		After MMA		*P* Value
	Mean	SD	Mean	SD	
Inspiration pressure, Pa	–529.46	788.03	–88.75	43.25	.006
Log inspiration pressure	2.51	0.40	1.90	0.23	.004
Inspiration velocity, m/s					
Nasal cavity	11.78	6.80	8.24	3.74	.091
Nasopharynx	4.69	3.00	3.05	1.55	.114
Retropalatal	19.30	20.39	6.59	6.45	.003
Retroglossal	11.26	7.89	5.23	2.13	.021

Abbreviation: MMA, maxillomandibular advancement.

Table 4. Pearson Correlation between Computational Fluid Dynamic and Polysomnography Parameters.

	ΔLog Pressure	ΔVelocity			
		Nasal Cavity	Nasopharynx	Retropalatal	Retroglossal
ΔAHI	0.348	–0.193	–0.018	0.617	0.556
P value	.295	.570	.958	.043	.076
ΔODI	0.566	–0.245	–0.062	0.773	0.502
P value	.070	.467	.856	.005[a]	.116
ΔLowest O_2%	–0.423	0.442	0.323	–0.831	–0.396
P value	.195	.173	.333	.002[a]	.228
ΔESS	–0.202	–0.199	–0.382	0.175	0.370
P value	.552	.558	.246	.607	.263

Abbreviations: AHI, apnea-hypopnea index; ESS, Epworth Sleepiness Scale; MMA, maxillomandibular advancement; ODI, oxygen desaturation index.
[a]$P < .01$.

and airflow velocity in the entire airway equalized (**Figure 4**). Our CFD study is an advancement from previous reports, with (1) greater number of subjects studied and (2) modeling of the entire upper airway from the nasal cavity to epiglottis.[23,25-28] More specific than previous reports concluding only global reduction in airflow velocity and negative pressure, ours found that velocity reduction at the narrowest part of the retropalatal airway is most correlated with surgical success.

Results from our study raise an important question about effective surgical treatment of OSA in general. Is the efficacy from MMA a result of maxillary advancement that enlarges retropalatal airway space, resulting in slower airflow velocity and less downstream negative pressure causing lateral pharyngeal wall collapse? Or does maxillary advancement create tension and stabilization of the lateral pharyngeal wall, a particularly difficult part of the OSA airway to address? There likely is contribution from both mechanisms, as one reflects airflow dynamics and the other addresses airway stability.

The study certainly needs greater power to confirm current findings and address the mechanistic hypotheses just raised. Nontheoretical dynamic airflow measurements during sleep would be ideal to further validate CFD modeling. Our cohort had relatively uniform body mass index (overweight), and subjects with significant facial skeletal dysmorphism requiring combined orthodontic and surgical treatment were excluded. This limits the generalizability of our findings. We made certain that the subjects had PSG performed in the same institution before and after surgery for appropriate comparison of perioperative parameters, particularly with definition of hypopneas. This study can be strengthened in a prospective nature with both postoperative DISE and CT scan performed at the same time with PSG at 6 months after MMA. Finally, long-term follow-up of dynamic airway and airflow characteristics is critical for understanding relapse of disease severity.

Conclusion

MMA is an effective surgical option for patients who cannot tolerate positive airway pressure therapy, particularly those with severe lateral pharyngeal wall collapse seen on DISE. When examined dynamically via CFD modeling and DISE, improvement post-MMA as measured by AHI and ODI is best correlated with (1) decreased retropalatal airflow velocity and (2) increased lateral pharyngeal wall stability.

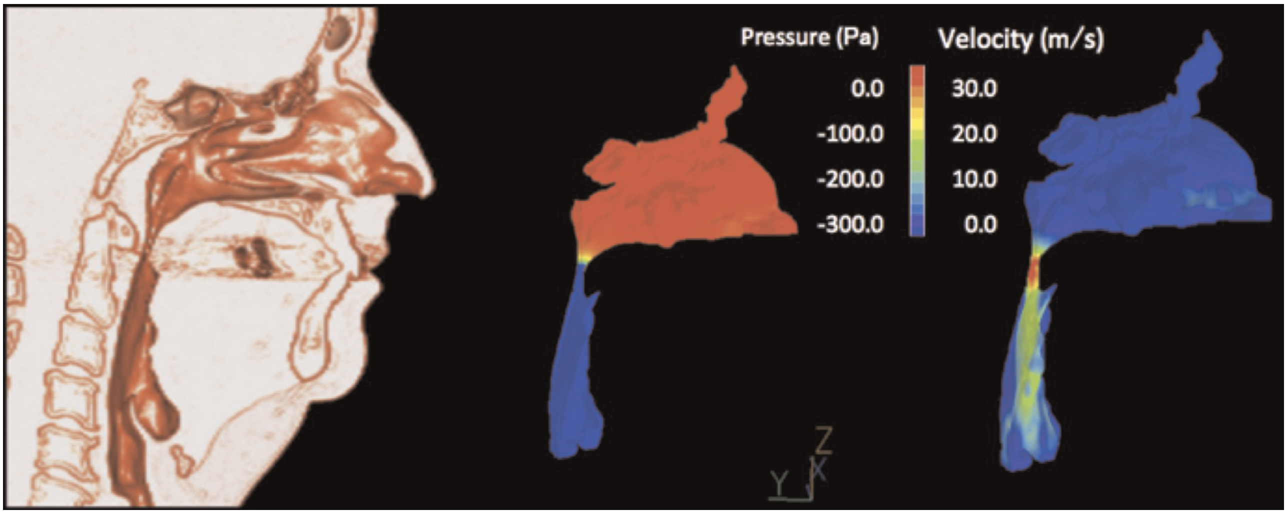

Figure 3. Computational fluid dynamics airway modeling before maxillomandibular advancement: velocity of airflow is highest at the retropalatal portion of the airway (>30 m/s), associated with negative pressure >300 Pa in the oropharynx during inspiration.

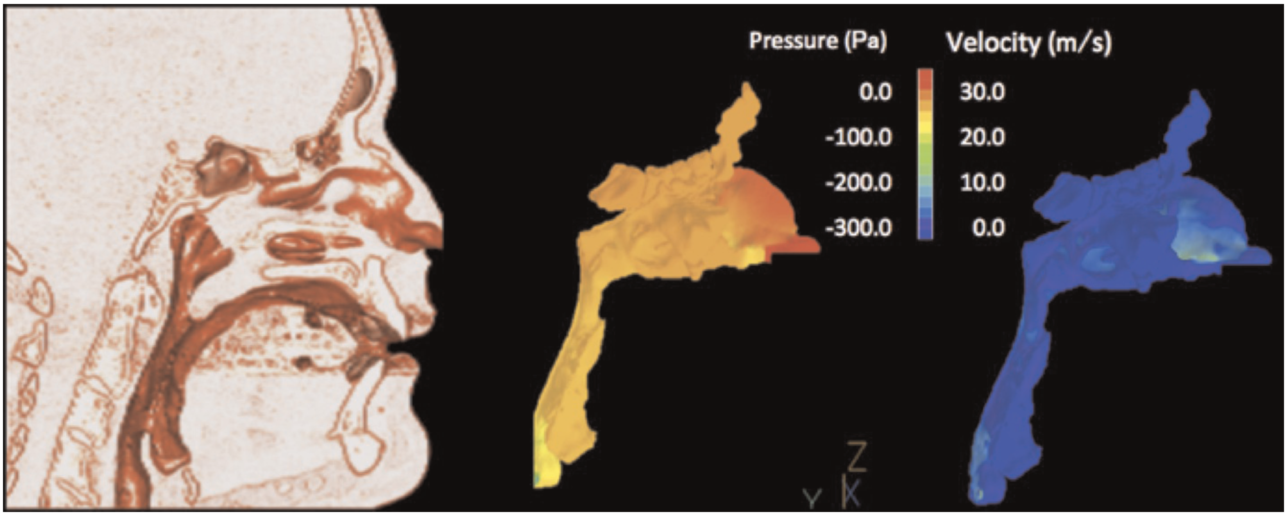

Figure 4. Computational fluid dynamics airway modeling before maxillomandibular advancement: velocity of airflow and pressure along the airway is equalized with resolution of retropalatal collapse.

Author Contributions

Stanley Yung-Chuan Liu, data collection, data interpretation, revising, final approval, responsibility for content of article; **Leh-Kiong Huon**, preliminary data analysis, measurement, drafting, revising, final approval; **Tomonori Iwasaki**, preliminary data analysis, measurement, drafting, revising, final approval; **Audrey Yoon**, data collection, data interpretation, measurement, revising, final approval; **Robert Riley**, revising, responsibility for content of article, final approval; **Nelson Powell**, revising, responsibility for content of article, final approval; **Carlos Torre**, data collection, data interpretation, revising, final approval; **Robson Capasso**, data collection, data interpretation, revising, final approval.

Disclosures

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Supplemental Material

Additional supporting information may be found at http://otojournal.org/supplemental.

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