

Mouth Puffing Phenomenon and Upper Airway Features May Be Used to Predict the Severity of Obstructive Sleep Apnea

Je-Yang Jau¹, Terry BJ Kuo^{1,3}, Lieber PH Li^{1,4-6}, Tien-Yu Chen^{1,7}, Ying-Shuo Hsu^{1,8,9}, Chun-Ting Lai^{1,2}, Weng-Cheu Yue¹⁰, Pin-Hsuan Huang¹¹, Cheryl CH Yang^{12,13}

¹Institute of Brain Science, National Yang-Ming Chiao-Tung University, Taipei, Taiwan; ²Sleep Research Center, National Yang Ming Chiao Tung University, Taipei, Taiwan; ³Tsoutun Psychiatric Center, Ministry of Health and Welfare, Nantou, Taiwan; ⁴Department of Otolaryngology, Cheng Hsin General Hospital, Taipei, Taiwan; ⁵Department of Medical Research, China Medical University Hospital, China Medical University, Taichung, Taiwan; ⁶Department of Speech Language Pathology and Audiology, College of Health Technology, National Taipei University of Nursing and Health Sciences, Taipei, Taiwan; ⁷Department of Psychiatry, Tri-Service General Hospital, School of Medicine, National Defense Medical Center, Taipei, Taiwan; ⁸Department of Otolaryngology, Shin Kong Wu Ho-Su Memorial Hospital, Taipei, Taiwan; ⁹School of Medicine, Fu Jen Catholic University, New Taipei City, Taiwan; ¹⁰DP Dental, Singapore; ¹¹Department of Health Promotion and Health Education, National Taiwan Normal University, Taipei, Taiwan; ¹²Department of Education and Research, Taipei City Hospital, Taipei, Taiwan; ¹³Brain Research Center, National Yang Ming Chiao Tung University, Taipei, Taiwan

Correspondence: Cheryl CH Yang, Institute of Brain Science, National Yang-Ming Chiao-Tung University, No. 155, Sec. 2, Li-Nong St., Beitou, Taipei, 11221, Taiwan, Tel +886-2-28267058, Fax +886-2-28273123, Email cchyang@ym.edu.tw; Lieber PH Li, Department of Otolaryngology, Cheng Hsin General Hospital, No. 45, Cheng Hsin St., Beitou, Taipei, 11221, Taiwan, Tel +886-2-28264400, Email lieber.chgh@gmail.com

Purpose: This study aimed to investigate (1) the role of mouth puffing phenomenon and upper airway features in obstructive sleep apnea (OSA) and (2) whether mouth-taping during sleep alleviated the severity of OSA.

Participants and Methods: Seventy-one participants underwent a two-night home sleep test (the first day sleeping normally; the second day sleeping with their mouths being taped); their oximetry desaturation index (ODI) and mouth puffing signals (non-mouth puffing, complete mouth puffing, intermittent mouth puffing (IMP), and side mouth puffing) were detected by a validated fingertip pulse oximeter and a mouth puffing detector. The participants were grouped into the ODI-improved group and the ODI-not-improved group according to their sleeping test results. The radiograph was taken by cone-beam computed tomography and cephalometries. Upper airway features including airways, soft tissues, and oral cavity variables were measured.

Results: Participants with severe OSA showed a higher IMP percentage compared with those with normal, mild, and moderate OSA (severe: 33.78%, moderate: 22.38%, mild: 14.55%, normal: 0.31%, $p < 0.001$). In all participants, the ODI and the percentage of SpO₂ under 90 (T90) were positively related to body mass index (BMI) ($r = 0.310$ and 0.333 , respectively), while ODI and T90 were negatively correlated with the minimum width of the airway ($r = -0.473$ and -0.474 , respectively); all mentioned relationships were significant ($p < 0.05$).

Conclusion: IMP proportions were found to be higher in the half of participants whose ODI did not improve after mouth-taping and in those with severe OSA. Moreover, OSA patients with higher ODI, higher T90, and higher proportions of IMP were more likely to have a narrower upper airway.

Keywords: mouth breathing, mouth puffing, sleep phenomena, oximeter, sleep apnea, accelerometer

Introduction

Obstructive sleep apnea (OSA) is a common sleep disorder wherein there is a recurrent resistance to the breathing of patients during sleep. Loud snoring, gasping during sleep, obesity, and enlarged neck circumference are risk factors for OSA.¹ The exact prevalence is unknown but estimated to be 2–14%.² This disorder is characterized by repetitive episodes of airway obstruction, resulting in decreased airflow despite ongoing respiratory efforts during sleep, which suggests that recurrent collapse of the upper airway during sleep might be the most important factor for OSA.³

OSA patients had a significantly smaller average airway area and average airway volume compared with non-OSA subjects.^{2,4} The craniofacial abnormalities that are most associated with OSA are mandibular deficiency, maxillary hypoplasia, the inferior position of the hyoid bone, a narrowed posterior air space, and a greater flexion of the cranial base.^{5–7} Overall, different oromandibular structures may affect the size of the soft tissues of the oropharynx, and when the soft tissues of the oropharynx are so large that they compress the space of the upper airway, it is likely that sleep apnea occurs. Breathing with the mouth open during sleep is a common phenomenon for patients with OSA.⁸ A previous study found that keeping the mouth open resulted in a prolonged airway and shrank the oropharyngeal lumen irrespective of the severity of OSA. Simultaneously, sleeping with the mouth wide open combined with larger tonsils contributes to a narrower oropharyngeal airway.⁹ A recent study showed that people breathing through their mouths might have a more elongated and narrower upper airway, increasing the pharyngeal resistance and the collapse of the pharyngeal airway, thus increasing the OSA severity.^{3–5} Moreover, mouth breathing has been related to hypoxia, and patients with OSA who have mouth breathing symptoms can have a relatively high chance of being hypoxemic.^{6,7}

Mouth breathing has been identified as a risk factor for OSA in recent years. For this reason, oral devices or mouth-taping have been used to avoid mouth breathing. The porous oral patch is a useful device to reduce snoring severity and can improve the apnea/hypopnea index (AHI) in patients with mild OSA and those who habitually mouth-breathe during sleep, regardless of the body mass index (BMI) of the patients.¹⁰ A previous study showed that using a porous oral patch, a mandibular advancement device (MAD), a continuous positive airway pressure (CPAP, the gold standard for treating OSA), or other oral devices to prevent mouth breathing had improved the AHI of OSA patients and their other sleep-disordered symptoms.^{1,10,11} However, the AHI of one-third of the participants became worse in the study by Huang,¹⁰ indicating that the device to prevent mouth breathing may not be suitable for every OSA patient and can even make OSA symptoms worse for reasons that need further investigations. Clinically, the condition of a patient with OSA was found to worsen after being mouth taped during sleep. After an otorhinolaryngological check-up, a mouth puffing phenomenon was observed when the patient was asleep, indicating that the patient was trying to breathe through the mouth despite that the oral device was preventing them to do so. In our previous study, the mouth puffing phenomenon had been observed and detected by a mouth puffing detector (MPD) in participants during polysomnography.¹²

Therefore, it is important to clarify the correlation between the mouth puffing phenomenon and OSA. This study aimed to investigate (1) the role of mouth puffing phenomenon and upper airway features in obstructive sleep apnea (OSA), and (2) whether mouth-taping during sleep alleviated the severity of OSA.

Materials and Methods

Participants, Instrumentation, and Study Protocol

This study recruited 71 participants, aged from 35 to 60 years. Figure 1 shows the participant recruitment flowchart. All participants took the home sleep test for two consecutive nights. The wireless fingertip pulse oximeter (AT101C-XB, Taiwan) was attached to a finger to detect the SpO₂-related variables, the oxygen saturation signal, and physical activity data, which were gathered every second.¹³ It has an 81.25% accuracy in OSA diagnosis.¹³ To detect the phenomenon of mouth puffing when mouth-taped, the participants were asked to sleep with their mouths sealed by the breathable tape throughout the night (Figure 2). We have also developed a mouth puffing detector (MPD).^{12–14} It is the combination of two originally designed accelerometers (BLEACT, 7 g, 4.2×1.8 × 0.75 cm³, Taiwan) to record the ranges of mouth puffing. In the present study, the accelerometers were placed on both cheeks of the participants and fixed with tape (shown in Figure 2). According to the number of mouth puffing by minute, the mouth puffing signals (MPSs) were distinguished into four types, including non-mouth puffing (NMP), complete mouth puffing (CMP), intermittent mouth puffing (IMP), and side mouth breathing (SMP). Moreover, we obtained the basic information about the participants at their first intake, including their sex, age, height, weight, and neck circumference. We also collected their answers to the sleep-related scales, including Pittsburgh Sleep Quality Index (PSQI) and Epworth Sleepiness Scale (ESS). Participants with reported psychiatric diseases, neurological disorders, diabetes, chronic renal diseases, cancer, cardiovascular diseases (hypertension), cigarette or alcohol addiction, or sleep disorders were excluded. All participants had provided

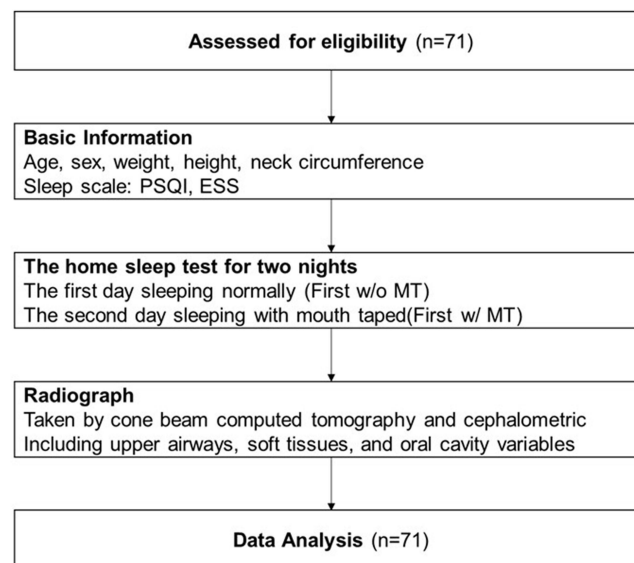


Figure 1 Flowchart summarizing the study procedure.

Abbreviations: PSQI, Pittsburgh Sleep Quality Index; ESS, Epworth Sleepiness Scale; w/o MT, when not mouth-taped; w/ MT, when mouth-taped.

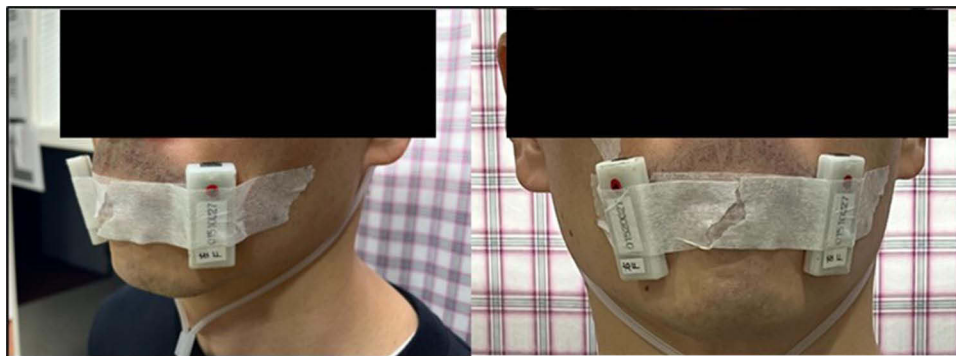


Figure 2 Images to demonstrate how the participants slept with their mouths sealed by the breathable tape throughout the night.

written informed consent. The procedures used in this study were approved by the Human Research Committee of the National Yang-Ming University, Taipei, Taiwan (YM107083E).

Upper Airway, Soft Tissue, and Oral Cavity Variables

All participants took the cone beam computed tomography and cephalometries, from which we measured their upper airways, soft tissues, and oral cavity variables. The followings are the descriptions of the measured variables (shown in [Figures 3 and 4](#)). Upper airway variables included the narrowest dimension between the posterior part of the uvula and the anterior wall of the nasopharynx (MTSP), the narrowest dimension between the posterior part of the tongue and the anterior wall of the oropharynx (MTIP), and the minimum width of the airway (MWA). Soft tissue variables included the distance between the hyoid bone to the mandibular plane (MP), and the length of the uvula (UL). The oral cavity consisted of variables coming from three dimensions. Sagittal variables included the mandible length (Co-Gn), and the angle between the sella-nasion and nasion-B point (SNB). Vertical variables included the anterior lower facial height (ANS-Me), and posterior facial height (S-Go). Transverse variables included the distance between the upper canine tips (U3W) and upper inter-molar width (U6W).

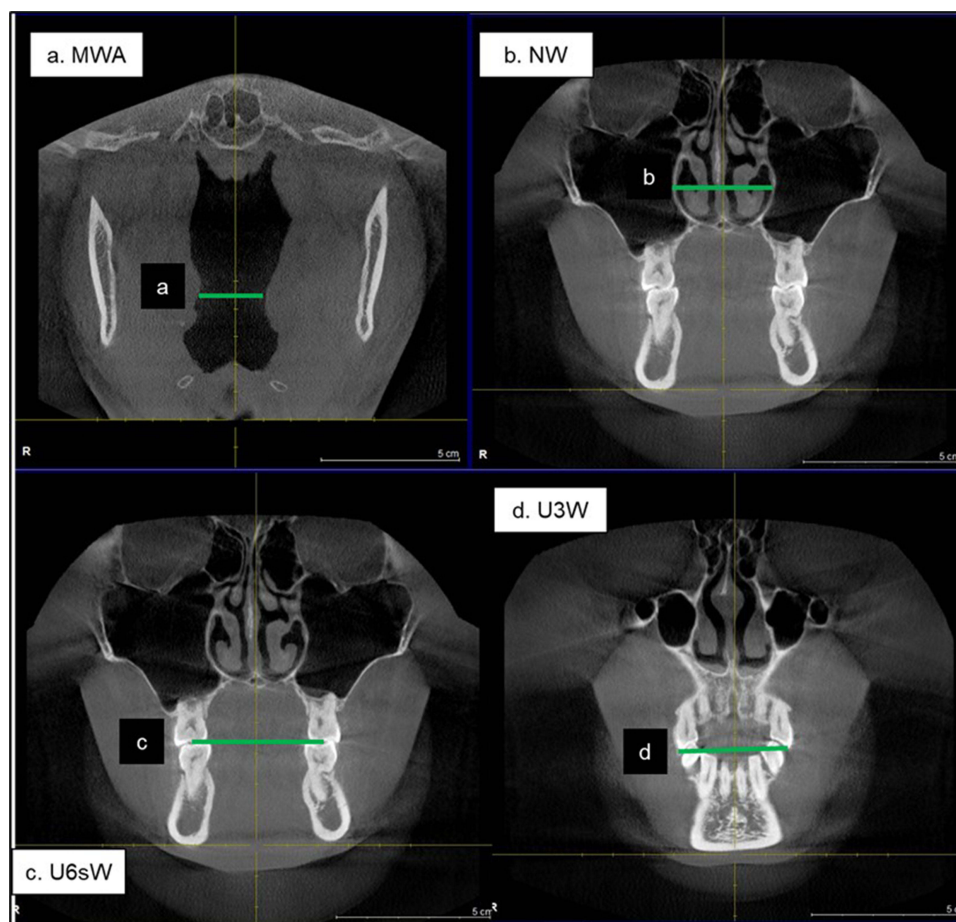


Figure 3 Measurements of the upper airway variables in CBCT images: transverse dimension variables of oral cavity variables in CBCT images.

Abbreviations: (a) MWA, minimum width of the airway; (b) NW, nasal width; (c) U6sW, upper inter-molar width; (d) U3W, the distance between the upper canine tips.

Statistical Analysis

Statistical analysis was performed using the SPSS software (24.0 version for Windows). For the statistical analysis of the present study, we first examined whether the variables were normally distributed. To compare the differences in the SpO₂-related variables and MPSs between the ODI-improved and ODI-not-improved groups, we used the independent sample *t*-test or Mann–Whitney *U*-test (if a variable was not normally distributed). The correlations of upper airway variables with the SpO₂-related variables and MPSs were analyzed with Pearson's correlation coefficient or Spearman correlation coefficient (if a variable was not normally distributed). The comparisons across the normal, mild, moderate, and severe OSA groups in terms of the SpO₂-related variables and MPSs were analyzed by the analysis of variance (ANOVA) with Scheffe's post-hoc test, if a variable was not normally distributed, then Kruskal–Wallis test with Dunn post-hoc test. Different biotypes, such as BMI and Angle's Classification, were also compared with ANOVA, if a variable was not normally distributed, then Kruskal–Wallis test with Dunn post-hoc test. For all analyses, $p < 0.05$ was considered statistically significant.

Results

Basic Information of Participants and Relationships of OSA Severity with SpO₂-Related Variables and MPSs

A total of 71 participants' (45 males and 13 females; mean age: 45.01 years old) MPSs, SpO₂ data, upper airway variables, and general information were collected. The mean BMI was 26.80, the mean neck circumference was 39.25 cm, the mean PSQI score was 8.63, and the mean ESS score was 10.75 (Table 1 and Table 2). All participants were classified into four

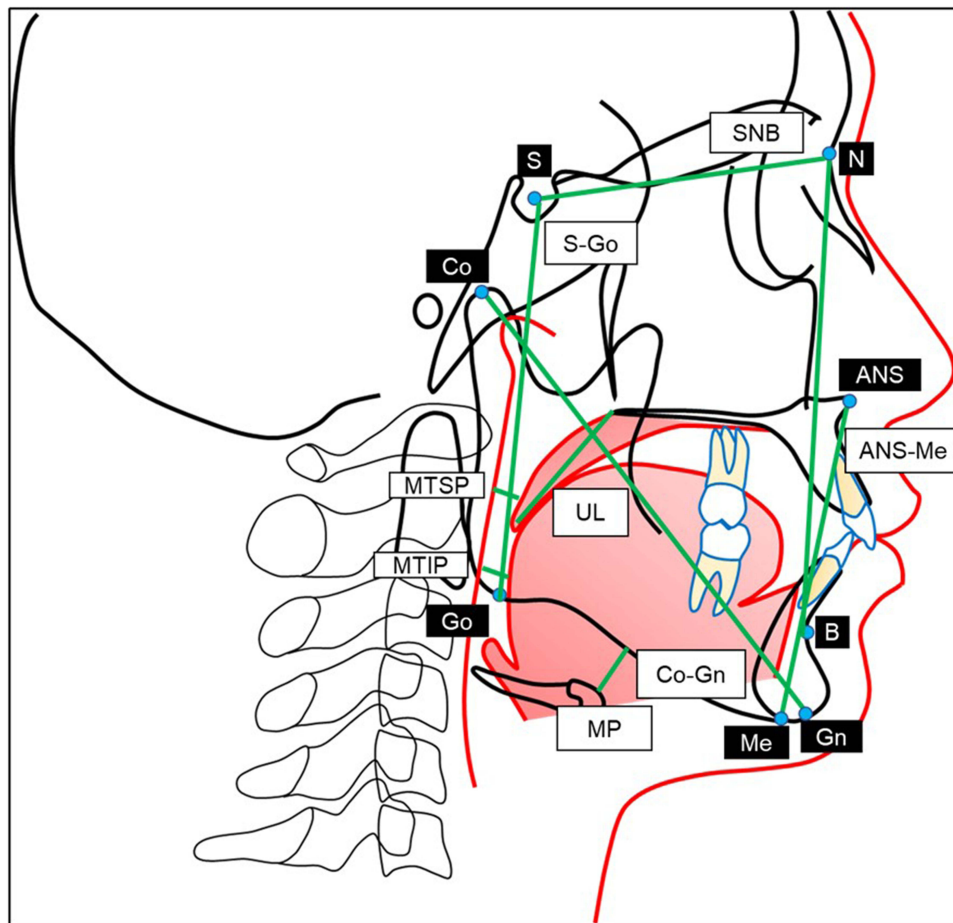


Figure 4 Sagittal and vertical dimension variables of the upper airway, soft tissue, and oral cavity in cephalometric images.

Abbreviations: MTSP, the narrowest dimension between the posterior part of the uvula and the anterior wall of the nasopharynx; MTIP, the narrowest dimension between the posterior part of the tongue and the anterior wall of the oropharynx; UL, length of uvula; MP, the distance between hyoid bone to mandibular plane; SNB, Angle between sella-nasion and nasion-B point; Co-Gn, Mandible length; ANS-Me, Anterior lower facial height; S-Go: Posterior facial height.

different OSA severity groups based on their ODI, there were 13 participants without OSA (Normal/control group), 17 participants with mild OSA, 28 participants with moderate OSA, and 13 participants with severe OSA. In Table 1, Kruskal–Wallis test of variance and Dunn post-hoc test. BMI, Neck circumference, PSQI, ODI, T90, mean SpO₂, the minimum SpO₂, NMP, IMP, CMP, and SMP of the four groups were found to be significantly different.

Comparing the ODI-Improved Group and the ODI-Not-Improved Group When Mouth-Taped

Table 2 shows that the ODI of 30 participants improved (51.72%, ODI-improved group/Group 1) when mouth-taped compared with when not, while those of the other 28 participants did not (48.28%, ODI-not-improved group/Group 2). Comparing the two groups when mouth-taped, only the ODI was statistically different ($p = 0.001$), with the mean ODI of Group 1 (16.37) significantly lower than that of Group 2 (30.50); further, a significant difference ($p = 0.037$) was found between the two groups in terms of their IMP ratios (Group 1: 19.06; Group 2: 26.47). On the other hand, comparing the two groups when not mouth-taped, none of the four SpO₂-related variables was found to be statistically different between Group 1 and Group 2.

Correlation Between the SpO₂-Related Variables and MPS Variables of Participants When Not Mouth-Taped

Table 2 shows the correlation between SpO₂-related variables and MPS variables. IMP ratio was moderately positively correlated with ODI ($r = 0.56$, $p < 0.05$) and T90 ($r = 0.45$, $p < 0.001$), IMP ratio was negatively correlated with mean

Table 1 Compare the ODI Improved Group and the ODI Not-Improved Group After Mouth-Taped

	All (N=58)	ODI Improved Group (n=30)	ODI Not-Improved Group (n=28)	p-value
Gender, male (%)	45 (77.6)	21 (70)	24 (85.7)	0.157
Age (year)	46.02±7.16	44.63±7.84	47.50±6.16	0.129
Body mass index	27.77±4.70	27.17±4.74	28.33±4.68	0.373
Neck circumference	40.41±3.88	39.82±3.78	40.95±3.96	0.292
PSQI	8.06±2.80	8.42±2.80	7.68±2.81	0.349
ESS	10.92±3.58	10.58±3.80	11.28±3.39	0.489
w/o MT_ODI (per hour)	23.79±14.90	24.94±15.72	22.55±14.16	0.546
w/o MT_Mean SpO ₂ (%)	95.35±1.90	95.60±1.98	95.08±1.82	0.306
w/o MT_Minimum SpO ₂ (%)	76.47±7.81	75.77±7.46	77.21±8.24	0.485
w/o MT_T 90 (%)	6.18±10.08	6.09±11.36	6.29±8.70	0.939
MT_ODI (per hour)	23.19±17.02	16.37±13.83	30.50±17.30	0.001*
MT_Mean SpO ₂ (%)	95.26±1.75	95.68±1.64	94.81±1.79	0.058
MT_Minimum SpO ₂ (%)	75.21±7.84	75.40±7.62	75.00±8.20	0.848
MT_T 90 (%)	6.16±8.86	4.38±8.30	8.06±9.20	0.114
NMP (%)	51.35±25.71	54.47±27.86	48.00±23.21	0.343
IMP (%)	22.64±13.63	19.06±11.88	26.47±14.53	0.037*
CMP (%)	6.97±11.02	8.31±13.28	5.53±7.91	0.341
SMP (%)	19.05±13.66	18.17±14.12	20.00±13.34	0.615

Notes: Data are presented as mean ± SD; * p-value < 0.05.

Abbreviations: w/o MT, when not mouth-taped; MT, when mouth-taped; T90, percentage of SpO₂ under 90; NMP, non-mouth puffing; IMP, intermittent mouth puffing; CMP, complete mouth puffing; SMP, side mouth puffing.

Table 2 Correlation Between the SpO₂-Related Variables and MPS Variables of Participants When Not Mouth-Taped

	ODI (Events/Hour)	Mean SpO ₂ (%)	Minimum SpO ₂ (%)	T 90 (%)
NMP (%)	-0.45 ^b	0.50 ^b	0.27 ^a	-0.39 ^b
IMP (%)	0.56 ^b	-0.55 ^b	-0.33 ^a	0.45 ^b
CMP (%)	0.004	-0.13	-0.08	0.03
SMP (%)	0.29 ^a	-0.29 ^a	-0.11	0.25

Note: ^ap < 0.05; ^bp < 0.001.

Abbreviations: ODI, oxygen desaturation index; T90, percentage of SpO₂ under 90; NMP, non-mouth puffing; IMP, Intermittent mouth puffing; CMP, complete mouth puffing; SMP, side mouth puffing.

SpO₂ ($r = -0.55$, $p < 0.001$) and the minimum SpO₂ ($r = -0.33$, $p < 0.05$), NMP ratio was negatively correlated with ODI ($r = -0.45$, $p < 0.001$) and T90 ($r = -0.39$, $p < 0.001$), and NMP ratio was positively correlated with mean SpO₂ ($r = 0.50$, $p < 0.001$) and the minimum SpO₂ ($r = 0.27$, $p < 0.05$). In short, ODI and T90 of the participants were positively correlated with the proportion of IMP and were negatively related to the proportion of NMP.

Correlations of the SpO₂-Related Variables with Upper Airway, Soft Tissue, and Oral Cavity Variables

Table 3 presents the correlations of the SpO₂-related variables with the upper airway, soft tissue, and three-dimensional oral cavity variables, among which was the soft tissue most related to SpO₂. The proportion of IMP was significantly positively related to soft tissue, implying that OSA patients with a higher proportion of IMP had larger uvula ($r = 0.301$, $p < 0.05$). ODI was negatively related to the minimum width of the airway ($r = -0.473$, $p < 0.001$) and nasal width ($r = -0.381$, $p < 0.001$). T90 was significantly negatively related to the minimum width of the airway ($r = -0.474$, $p < 0.001$)

Table 3 The Data from All the Participants are Categorized into Four MPSs to Assess the Difference in SpO₂-Related Variables by Minutes

	All Data (n=19,270)	SMP (n=3526)	CMP (n=1107)	NMP (n=10,357)	IMP (n=4280)	p-value
ODI (events/min)	0.37 ± 0.64	0.41 ± 0.68	0.26 ± 0.56 ^a	0.27 ± 0.55 ^a	0.61 ± 0.77 ^{abc}	<0.001**
Mean SpO ₂ (%)	95.29 ± 3.20	95.01 ± 3.20	95.11 ± 2.96	95.91 ± 2.81 ^{ab}	94.05 ± 3.71 ^{abc}	<0.001**
T90 (%)	3.83 ± 11.55	4.41 ± 12.16	3.63 ± 11.74	2.13 ± 8.90 ^{ab}	7.51 ± 15.18 ^{abc}	<0.001**
SpO ₂ _STD	1.12 ± 1.29	1.19 ± 1.37	0.87 ± 1.07 ^a	0.90 ± 1.08 ^a	1.66 ± 1.56 ^{abc}	<0.001**

Notes: Data are presented as mean ± SD; n indicates the number of data by minutes; Analysis of variance and Scheffe's post-hoc tests are used. ^aCompared with side mouth puffing (SMP); ^bCompared with complete mouth breathing (CMP); ^cCompared with complete mouth breathing (NMP); p < 0.001**.

Abbreviations: ODI, oxygen desaturation index; T90, percentage of SpO₂ under 90; SpO₂_STD, standard deviation of SpO₂ in minute; NMP, non-mouth puffing; IMP, Intermittent mouth puffing; CMP, complete mouth puffing; SMP, side mouth puffing.

and nasal width ($r = -0.316$, $p < 0.001$). In terms of the oral cavity variables, SpO₂-related variables were not statistically related to the oral cavity variables. In addition, ODI, T90, and the proportion of MPS were significantly related to BMI and neck circumference, such that OSA patients with higher ODI, higher T90, and higher proportions of MPS were more likely to have a narrower upper airway, greater soft tissue, a thicker neck, and an overweight body.

Discussion

This study evaluated the relationships between different mouth puffing phenomena and the severity of OSA. Several novel findings were noticed in the study. ODI in half of the participants deteriorated after they were mouth-taped during sleep. The percentage of IMP was found to be positively associated with OSA severity.

The present study revealed the relationship between MPSs and OSA severity. Higher percentage of IMP, lower percentage of NMP, higher ODI and T90, and lower mean SpO₂ were significantly correlated. This signified that mouth breathing, especially IMP, was related to ODI severity. Recent studies showed that patients with a higher percentage of oral and oronasal breathing periods had severer OSA and lower SpO₂ than common snorers and healthy subjects did.^{4,6,8,15} Previous studies showed that participants who completely breathed with the nose (NMP) tended to have more stable SpO₂ during sleep,^{4,7,8} which is consistent with the findings of the present study. However, in we further classified mouth puffing into IMP, CMP, and SMP. IMP was the worst breathing pattern and was correlated with OSA severity the most (Table S1). While CMP and NMP are both types of regular breathing, the former was found to be more positively correlated with lower SpO₂ than the latter, implying that CMP was a worse breathing pattern than NMP. SMP came in different values because of external influences (eg, sleep posture), which should be further explored in the future. Blood oxygen was found to be higher during SMP than during IMP, probably due to the patient's attempt to move their body as a reaction to the respiratory obstruction. In short, IMP could be used as a mouth breathing severity index (MPSI) to assist in the diagnosis of OSA.

We also investigated the relationships between different biotypes and OSA, including BMI (Table 4) and Angle's Classification (Table S2). We divided BMI into three groups—normal, overweight, and obese; we found that the higher the BMI value, the severer OSA and the higher the proportion of IMP the participants had. Concerning the Angle's Classification, significant between-group differences were found only for the ANB angle.

There have been several previous studies on the relationship between palate structure and OSA, but there have been rare studies that investigated the relationship between stomatognathic structure and mouth breathing. In the present study, we found that OSA patients tended to have a narrower upper airway. This finding is consistent with the findings of previous studies, stating that the soft tissues of OSA patients are characterized by narrow posterior palate and posterior tongue airway space, thicker and longer soft palate, smaller angle between the tip of the uvula and the anterior nasal spine, and larger tongue. Oral breathing is a common phenomenon of OSA patients during sleep and it occurs more frequently right before and after events of apnea and hypopnea.^{16–18} Past studies have shown that mouth breathing tends to cause airway collapse and is associated with more serious and prevalent lateral pharyngeal wall collapse and tongue base collapse.⁴ For example, when viewed from the front posterior, the face and anterior cranial base of patients with OSA tended to shrink posteriorly, reducing the cranial base angle, and resulting in less available airway space. The

Table 4 Correlation Between the SpO₂-Related Variables and Basic Information/Upper Airway/Stomatognathic Structure Variables

	w/o MT_ODI	MT ODI	MT T90	NMP	IMP	CMP	SMP
Age	0.022	0.003	-0.091	-0.011	0.158	-0.131	0.130
Gender	0.117	0.234	0.188	0.124	-0.099	-0.163	0.264 ^a
Body mass index	0.424 ^b	0.390 ^b	0.355 ^b	0.280 ^a	0.324 ^a	-0.456 ^b	0.314 ^b
Neck circumference	0.306 ^a	0.310 ^a	0.300 ^a	0.333 ^a	0.130	-0.387 ^b	0.295 ^a
MTSP	-0.023	-0.014	-0.042	-0.076	-0.054	-0.028	0.174
MTIP	-0.018	-0.176	-0.118	-0.113	0.171	-0.010	-0.029
MASP	-0.216	-0.365 ^a	-0.281	-0.200	-0.034	0.252	-0.247
MAIP	-0.082	-0.239	-0.222	-0.044	0.156	0.013	-0.127
MWA	-0.357 ^a	-0.473 ^b	-0.474 ^b	-0.071	-0.087	0.284	-0.376 ^a
MP	0.248	0.276	0.376 ^a	0.275	0.014	-0.312 ^a	0.312
UL	0.230	0.209	0.224	0.333 ^a	0.301 ^a	-0.335 ^a	0.040
Co-Gn	-0.100	-0.117	-0.080	-0.341 ^a	-0.003	0.202	-0.052
SNB	-0.165	-0.085	-0.181	-0.391 ^a	0.028	0.262	-0.147
ANS-Me	0.113	0.174	0.170	-0.115	0.024	-0.013	0.113
S-Go	-0.177	-0.185	-0.129	-0.299 ^a	0.011	0.147	0.001
U6sVW	0.055	0.138	0.140	0.040	-0.116	0.052	-0.032
U3W	-0.061	-0.249	-0.112	0.025	-0.068	0.089	-0.130
Nasal width	-0.201	-0.381 ^b	-0.316 ^b	-0.045	0.028	0.066	-0.106

Note: ^ap < 0.05; ^bp < 0.001.

Abbreviations: ODI, oxygen desaturation index; T90, percentage of SpO₂ under 90; NMP, non- mouth puffing; IMP, Intermittent mouth puffing; CMP, complete mouth puffing; SMP, side mouth puffing; MTSP, the narrowest dimension between the posterior part of the uvula and the anterior wall of the nasopharynx; MTIP, the narrowest dimension between the posterior part of the tongue and the anterior wall of the oropharynx; MASP, minimum cross-sectional area of post-uvula; MAIP, minimum cross-sectional area of post-tongue; MWA, minimum width of airway; UL, length of uvula; MP, the distance between hyoid bone to mandibular plane; Co-Gn, Mandible length; SNB, Angle between sella-nasion and nasion-B point; ANS-Me, Anterior Lower Face Height; S-Go, Posterior facial height; U6sVW, upper inter-molar width; U3W, the distance between the upper canine tips; NW, nasal width.

inconsistency in the findings between the present study and previous studies might be due to differences in sample size: smaller in ours and larger in previous studies.

Although MPD is not a defined detection tool as Out-of-Center Sleep Testing (OCST), it complements the latter in the aspect of mouth puffing. Traditionally, OCST detects OSA by monitoring airflow, respiratory effort, and blood oxygenation. However, according to our explorations in the dental clinic, we discovered the association between mouth puffing and OSA severity, which then became the topic of our published article.¹² This previous study took place in the sleep center, through which we confirmed the significant and positive correlation between the frequency of mouth puffing and OSA severity and the accuracy of MPD in detecting mouth puffing based on the comparison with the polysomnography results. Now in the present study, we aimed to investigate whether these two findings were still consistent based on the home sleep apnea test. In short, MPD is as convenient as OCST, since it is also portable, and it detects OSA from a different angle, which OCST does not look at.

In recent years, more studies have investigated therapies to alleviate OSA symptoms, such as continuous positive airway pressure, MAD, porous oral patch, and others.^{1,10,11,19} A study from Japan demonstrated a device for continuous tongue suction as a potential therapy,¹⁹ which shed light on the necessity to design an effective device for keeping the tongue flat against the palate to alleviate OSA, further implying that myofunctional therapy (oropharyngeal exercises) could be an alternative OSA therapy.^{20,21} In other words, more studies on healthy individuals without OSA are needed to investigate whether MPSs, BMI, neck circumference, tongue pressure, sleep habits, and other variables are still highly correlated with ODI, and whether the tongue function training, an MAD, or other oral appliances can truly alleviate MPSs and ODI.

There are several limitations to our study. First, the sample size of the present study was rather small, making it inappropriate to generalize the findings to all populations. However, it was also due to the small sample size that we could obtain more detailed information about each participant, such as their SpO₂-related variables, cone-beam computed

tomography, and mouth puffing signals, and observe the relationships among them. Another limitation resulting from the small sample size was that it was easy for the immature MPS-detecting program to generate an overfitting model. If there had been more data collected, the model could have been trained to analyze MPSs without manually adjusting the parameters and come up with more accurate study results. For the current MPS-detecting program, we still needed to manually adjust the parameters, yet by observing the collected signals, we could further understand the facial movements of the participants during different sleep stages, such as yawning, coughing, etc., which can be included in future analysis. Finally, this was a cross-sectional study that could only suggest a correlation between MPSs and OSA and could not explain the cause and effect between the two.

Conclusion

MPD could effectively detect the mouth puffing phenomenon during sleep when mouth-taped and verify the effects of four types of MPSs, especially those of IMP, which was found to have a positive correlation with ODI and narrower upper airway. In the present study, we found that the mouth puffing phenomenon and OSA had a close correlation.

Abbreviations

OSA, obstructive sleep apnea; ODI, oxygen desaturation index; MPD, mouth puffing detector; IMP, intermittent mouth puffing; NMP, non-mouth puffing; AHI, apnea-hypopnea index; MPS, mouth puffing signal; CMP, complete mouth puffing; SMP, side mouth puffing; SpO₂, oxygen saturation; T90, percentage of SpO₂ under 90; PSQI, Pittsburgh Sleep Quality Index; ESS, Epworth Sleepiness Scale; MTSP, the narrowest dimension between the posterior part of the uvula and the anterior wall of the nasopharynx; MTIP, the narrowest dimension between the posterior part of the tongue and the anterior wall of the oropharynx; MWA, minimum width of the airway; NW, nasal width; U6sW, upper inter-molar width; U3W, the distance between the upper canine tips; UL, length of uvula; MP, the distance between hyoid bone to mandibular plane; SNB, Angle between sella-nasion and nasion-B point; Co-Gn, Mandible length; ANS-Me, Anterior lower facial height; S-Go, Posterior facial height.

Ethical Approval

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. The study was approved by the Human Research Committee of the National Yang-Ming University, Taipei, Taiwan (project number YM107083E).

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Disclosure

The authors report no conflicts of interest in this work.

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