Original Article

Three-dimensional analysis of upper airway morphology in skeletal Class III patients with and without mandibular asymmetry

Xi Wen[a]; Xiyu Wang[a]; Shuqi Qin[a]; Lorenzo Franchi[b]; Yan Gu[c]

ABSTRACT

Objective: To compare the three-dimensional (3D) morphology of the upper airway in skeletal Class III patients with and without mandibular asymmetry and to investigate the possible underlying correlations between the morphology of the upper airway and mandibular deviation.

Materials and Methods: Cone-beam computed tomography images of 54 subjects with skeletal Class III malocclusion (ANB angle $\leq 0.4°$, Wits $\leq -5.5°$) were taken and 3D upper airway models were reconstructed using Dolphin 3D software. According to the distance (d) from symphysis menti to the sagittal plane, all subjects were divided into a symmetry group ($d \leq 2$ mm) and an asymmetry group ($d \geq 4$ mm). Based on the severity of mandibular deviation, the asymmetry group was divided into subgroup I (4 mm $\leq d <$10 mm) and subgroup II ($d \geq 10$ mm). Cross-sectional linear distances, areas, and volumetric variables of the upper airway were measured in the 3D airway model.

Results: Width of the inferior limit of the glossopharynx (P3W), cross-sectional area of the anterior limit of the nasal airway (P5S), and height of the glossopharynx (GPH) in the asymmetry group were significantly larger than in the symmetry group. As for subjects with severe mandibular deviation in subgroup II ($d \geq 10$ mm), volume of the glossopharynx (GPV), total volume of the pharynx (TPV), length of the inferior limit of the velopharynx (P2L), and ratio of length to width of the inferior limit of the velopharynx (P2L/P2W) showed significantly negative correlations with mandibular deviation ($r > 0.7$, $P < .05$).

Conclusions: In Class III subjects with severe mandibular asymmetry, the pharyngeal airway showed a tendency toward constriction and presented a more elliptical shape as mandibular deviation became more severe ($P < .01$). (*Angle Orthod.* 2017;87:526–533)

KEY WORDS: Class III; Asymmetry; Upper airway morphology

INTRODUCTION

Studies have proven that obstruction of the upper airway is associated with a retrusive mandible, vertical growth pattern, and a Class II tendency.[1–5] Previous studies on airway morphology of patients with Class III malocclusion have been focused on the change of airway dimension after treatment with protraction headgear,[6] mandibular setback,[7,8,9] or bimaxillary surgery.[10] Ritcher et al.[11] reported two cases of obstructive sleep apnea syndrome found in asymmetrical patients, indicating that upper airway obstruction could exist in patients with mandibular asymmetry. Mandibular asymmetry was reported to most likely occur in Class III malocclusion, with a proportion of up to 25%–34%.[12,13] Knowing the characteristics of upper airway morphology of Class III patients with mandibular asymmetry is essential for an orthognathic surgeon when formulating a treatment plan for severe skeletal Class III patients due to the risk of upper airway obstruction.

[a] Postgraduate Student, Department of Orthodontics, National Engineering Laboratory for Digital and Material Technology of Stomatology; Beijing Key Laboratory of Digital Stomatology, Peking University School and Hospital of Stomatology, Beijing, People's Republic of China.

[b] Professor, Department of Orthodontics, University of Florence, Italy.

[c] Professor, Department of Orthodontics; National Engineering Laboratory for Digital and Material Technology of Stomatology; Beijing Key Laboratory of Digital Stomatology, Peking University School and Hospital of Stomatology, Beijing, People's Republic of China.

Corresponding author: Professor Yan Gu, Department of Orthodontics, Peking University School and Hospital of Stomatology, No. 22 ZhongGuanCun Nandajie, HaiDian District, Beijing 100081, People's Republic of China
(e-mail: guyan96@126.com)

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Traditional studies used two-dimensional techniques such as lateral cephalograms to analyze linear distances and morphology of the upper airway. This method has limitations since it allows only evaluating anteroposterior (AP) linear measurements in the sagittal plane with poor accuracy and cannot provide volumetric information on anirregularly shaped upper airway.[14] Cone-beam computed tomography (CBCT) uses a different radiation acquisition technique to obtain high-quality images with relatively low amounts of radiation.[4] Previous studies have proven that CBCT measurement has higher accuracy and reliability than traditional methods.[15,16] More importantly, 3D reconstruction of the upper airway structure based on CBCT makes accurate volumetric analysis possible.[4] Therefore, characteristics of the upper airway and cephalometric variables of skeletal Class III patients with and without asymmetry can be measured precisely by CBCT.[17,18] According to the imaging selection guideline recommended by the American Academy of Oral and Maxillofacial Radiology,[19] the use of large-field-of-view CBCT may be indicated in the pretreatment examination of asymmetrical patients for whom this procedure would have obvious benefits. Therefore, CBCT might be taken as part of the pretreatment examination of asymmetrical patients due to its advantages of providing high resolution and accuracy in diagnosis.

The aim of this study was to compare the 3D morphology of the upper airway in skeletal Class III patients with or without mandibular asymmetry and investigate the possible underlying correlations between the morphology of the upper airway and mandibular deviation.

MATERIALS AND METHODS

Subjects

All subjects were obtained from the Department of Orthognathic Surgery who presented with a severe skeletal Class III pattern, crossbite, and open bite. This study was approved by the Biomedical Ethics Committee of Peking University School and Hospital of Stomatology.

Inclusion and Exclusion Criteria

Inclusion criteria were (1) aged 16 years and above; (2) Mongolian; (3) skeletal Class III (ANB angle $\leq 0.4°$, Wits $\leq -5.5°$; Chinese norms of ANB $2.7° \pm 2.0°$,Wits norms $-0.8° \pm 2.8°$); (4) MP-SN $\geq 27°$; Chinese norms $32.5° \pm 5.2°$; (5) no congenitally missing teeth, retained deciduous teeth, or impacted teeth; (6) no orthodontic or orthognathic treatment; (7) no history of palatal or pharyngeal surgery; (8) no cleft lip or palate. Exclusion criteria were (1) pharyngeal or nasal pathology such as adenoid hypertrophy and OSAHS; (2) congenital disease; (3) mouth breathing.

Groups

As the primary outcome variable of the airway 3D analysis, we chose the width of the inferior limit of the glossopharynx (P3W). In a previous study,[4] a standard deviation of 3.1 mm was reported for P3W. If a clinically relevant difference for this variable is set at 2.5 mm, at least 26 subjects were determined to be needed per group to reject the null hypothesis that the population means of the asymmetric and symmetric groups were not different, with a probability (power) of 0.8. The type I error probability associated with this test of this null hypothesis was 0.05 PS Power and Sample Size Calculations, Version 3.0, http://creativecommons.org/licenses/by-nc-nd/3.0/us/"Creative Commons Attribution-NonCommercial-NoDerivs 3.0 United States License).

Fifty-four subjects with skeletal Class III malocclusion were involved in this study (38 females, 16 males, mean age 20.4 $\pm$ 2.7 years). According to the standard of Haraguchi et al.,[20] the subjects were divided into two groups based on the distance from symphysis menti to tthe sagittal plane measured on 3D CBCT images:

Symmetry group: 28 subjects (21 females, 7 males, mean age 21.5 $\pm$ 2.8 years) with a distance between 0 and 2 mm ($0 < d \leq 2$ mm) were included in the symmetry group with a mean deviation of 1.2 $\pm$ 0.7 mm.

Asymmetry group: 26 subjects (17 females, 9 males, mean age 19.9 $\pm$ 2.6 years) with a distance greater than 4 mm ($d \geq 4$ mm) were included in the asymmetry group with a mean deviation of 8.0 $\pm$ 3.3 mm.

No significant difference was noted between the symmetry and asymmetry groups regarding the average value of ANB, Wits, and MP-SN. The asymmetry group was further divided into two subgroups according to the severity of the mandibular deviation:

Subgroup I: Distance between 4 mm and 10 mm (4 mm $\leq d <$ 10 mm) (10 females, 6 males, mean age 20.0 $\pm$ 2.6 years)

Subgroup II: Distance greater than or equal to 10 mm ($d \geq 10$ mm) (7 females, 3 males, mean age 19.7 $\pm$ 2.7 years)

CBCT

CBCT images were taken with a NewTom Scanner (NewTom AG, Marburg, Germany) for the pretreatment examination. All images were taken at 2.81 mA, 110 kV, 3.6-second exposure, 15×15-cm field of view, with axial slice thickness of 0.3 mm, and isotropic voxels. Patients sat upright with a natural head position and jaws immobilized using a chin holder, keeping the Frankfort plane horizontal to the ground. The teeth were occluded in centric occlusion, with facial muscles relaxed. The patients were asked to breathe peacefully and to not swallow. The CBCT images were saved as

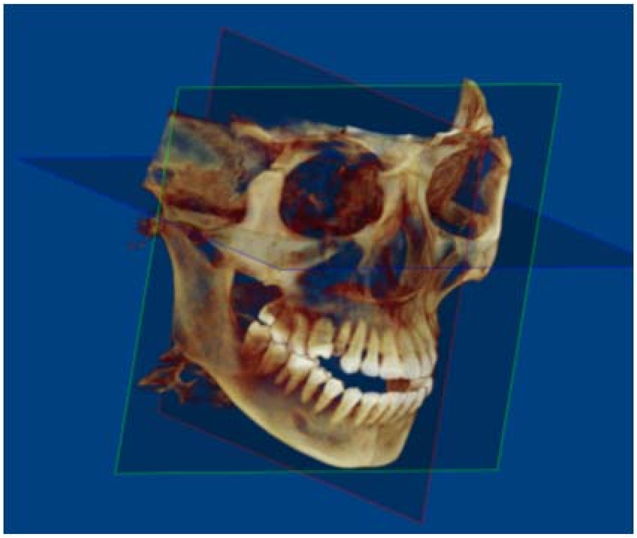

Figure 1. Horizontal, sagittal, and coronal reconstruction after head reorientation.

digital imaging and communications in medicine (DICOM) format and imported to the Dolphin 3D Imaging software (version 11.7, Dolphin Imaging and Management Solutions, Chatsworth, Calif)

On multiple planar reconstruction images, the skull was reoriented using the following guidelines: (1) The horizontal plane was defined as the Frankfort horizontal (FH) plane constructed through bilateral infraorbitale skeletal landmarks and right porion. (2) The sagittal plane was positioned through the midpoint of the clinoid process and nasion and perpendicular to FH. (3) The coronal plane was constructed perpendicular to the above two planes, passing through basion. Figure 1 illustrates the horizontal, sagittal, and coronal planes after head orientation.

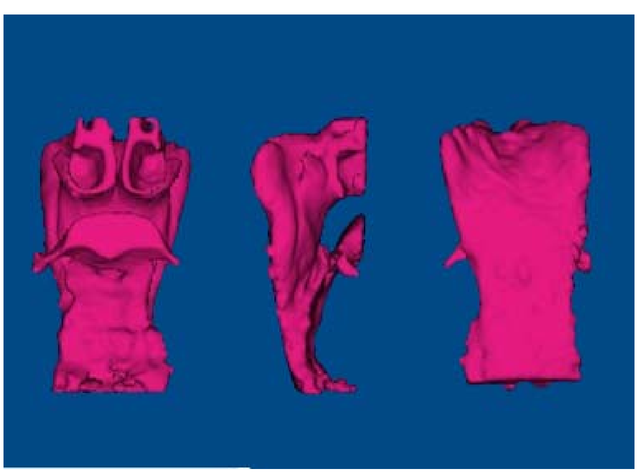

Figure 2. Frontal, lateral, and back view of the 3D reconstructed pharyngeal model.

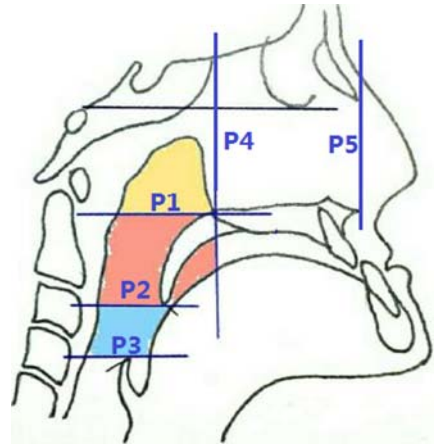

Figure 3. Segmentation of the upper airway: The pharyngeal airway was subdivided into three compartments by three planes (P1, P2, P3) horizontal to the FH plane including the posterior nasal spine (PNS), uvula top (UT) and epiglottis top (ET). The anterior and posterior limits of the nasal airway were defined by the planes P4 and P5 perpendicular to FH passing through the anterior nasal spine (ANS) and posterior nasal spine (PNS).

3D Upper Airway Reconstruction and Measurements

The 3D upper airway model was reconstructed in Dolphin 3D software (Figure 2). The upper airway was generally divided into two parts: pharyngeal airway and nasal airway. The pharyngeal airway was further divided into nasopharynx, velopharynx, and glossopharynx. The limits for segmentation are illustrated in Figure 3 and Table 1. Linear distance, area, and volume measurements were performed on the 3D airway model. Width,

Table 1. Anatomical Limits of Upper Airway

Subdivision of Airway	Definition
Nasal airway	Anterior limit: P5 perpendicular to FH passing through ANS Posterior limit: P4 perpendicular to FH passing through PNS Lateral limit: inner limit of the bony nasal wall
Nasopharynx	Superior limit: last slice before fusion of the nasal septum with the posterior wall of the pharynx Inferior limit: P1 parallel to FH passing through PNS
Velopharynx	Superior limit: inferior limit of the nasopharynx Inferior limit: P2 parallel to FH passing through the uvula top (UT) Anterior limit: P4 perpendicular to FH passing through PNS Lateral limit: soft tissue contour of the pharyngeal wall
Glossopharynx	Superior limit: inferior limit of the velopharynx Inferior limit: P3 parallel to FH passing through the epiglottis top (ET) Lateral limit: soft tissue contour of the pharyngeal wall

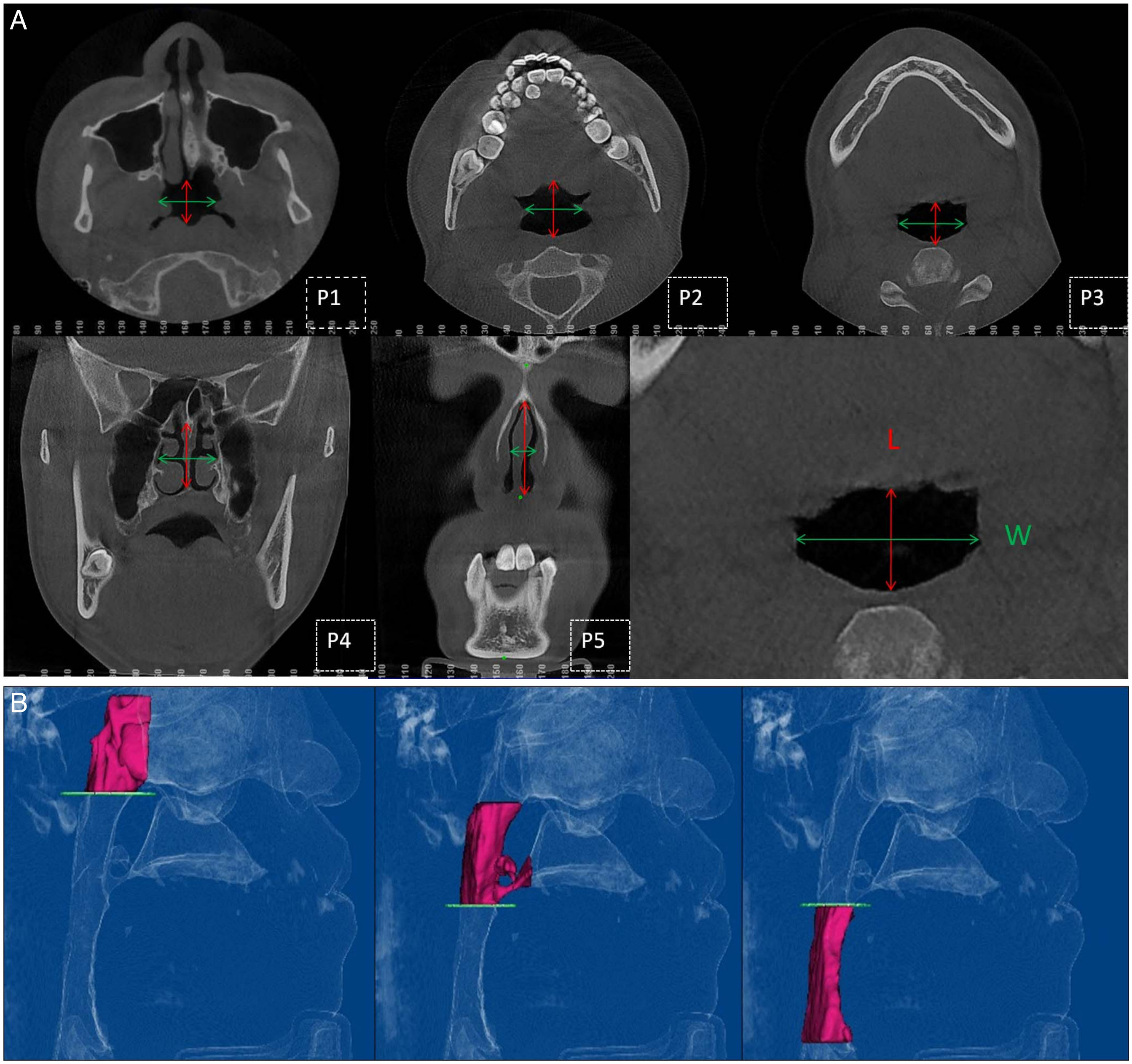

Figure 4. Cross-sectional linear distances, area, and volumetric measurements of the upper airway. (A) Cross-sectional linear distances of P1–P5. The red line (L) and green line (W) represent the length and width of the cross-sectional plane, respectively. (B) Volumetric measurements of the nasopharynx, velopharynx, and glossopharynx.

length, and area were measured and calculated in cross-sectional views of the upper airway, using a method initially proposed by Kim et al. (Figure 4 and Table 2).[4] The height of the pharyngeal airway was measured (Table 2) and the volume of each segmentation of upper airway was calculated (Table 2).

Statistical Analysis

Descriptive statistics were performed with SPSS software (version 19.0, SPSS, Chicago, Ill). Inter- and intraobserver reliability of upper airway measurements were calculated by intraclass correlation coefficients (ICCs) with a two-way random effect model. Normality of all variables was tested by the one-sample Komolgorov-Smirnov test. Differences between the symmetry and asymmetry groups were tested by independent-sample *t*-tests. Pearson correlation tests were used to evaluate the correlation between airway measurements and mandibular deviation. Differences were considered statistically significant when $P < .05$.

Table 2. Definitions of Upper Airway Landmarks

Measurement	Definition
1. Cross-sectional linear distance	
P1L	Greatest distance in the AP direction of P1
P1W	Horizontal distance of P1 passing through the midpoint of P1L
P2L	Greatest distance in the AP direction of P2
P2W	Horizontal distance of P2 passing through the midpoint of P2L
P3L	Greatest distance in the AP direction of P3
P3W	Horizontal distance of P3 passing through the midpoint of P3L
P4H	Greatest distance in the vertical direction of P4
P4W	Horizontal distance of P4 passing through the midpoint of P4L
P5H	Greatest distance in the vertical direction of P5
P5W	Horizontal distance of P5 passing through the midpoint of P5L
2. Cross-sectional area	
P1S	Cross-sectional area of P1
P2S	Cross-sectional area of P2
P3S	Cross-sectional area of P3
P4S	Cross-sectional area of P4
P5S	Cross-sectional area of P5
3. Cross-sectional ratio	
P1L/P1W	Ratio of P1L to P1W, representing the shape of P1
P2L/P2W	Ratio of P2L to P2W, representing the shape of P2
P3L/P3W	Ratio of P3L to P3W, representing the shape of P3
4. Upper airway height	
NPH	Vertical distance between the superior and inferior limits of the nasopharynx
VPH	Vertical distance between the superior and inferior limits of the velopharynx
GPH	Vertical distance between the superior and inferior limits of the glossopharynx
TPH	Vertical distance between the superior and inferior limits of the pharynx
5. Airway volume	
NV	Volume of nasal cavity
NPV	Volume of nasopharynx
VPV	Volume of velopharynx
GPV	Volume of glossopharynx
TPV	Total volume of pharynx
TV	Total volume of upper airway

Table 3. Intraclass Correlation Coefficients (ICCs) of Upper Airway Variables for Inter- and Intraobserver Reliability

	Interobserver		Intraobserver	
	Asymmetry	Symmetry	Asymmetry	Symmetry
P1L	0.994	0.940	0.978	0.948
P1W	0.962	0.988	0.913	0.890
P2L	0.990	0.838	0.984	0.893
P2W	0.909	0.886	0.913	0.852
P3L	0.768	0.898	0.933	0.968
P3W	0.980	0.959	0.959	0.956
P4H	0.782	0.762	0.821	0.750
P4W	0.998	0.929	0.923	0.881
P5H	0.954	0.802	0.937	0.868
P5W	0.808	0.930	0.785	0.808
P1S	0.764	0.776	0.835	0.945
P2S	0.955	0.894	0.952	0.918
P3S	0.985	0.935	0.871	0.925
P4S	0.976	0.900	0.958	0.893
P5S	0.860	0.802	0.913	0.852
NPH	0.927	0.987	0.897	0.967
VPH	0.994	0.834	0.996	0.802
GPH	0.995	0.989	0.995	0.990
NPV	0.991	0.976	0.993	0.966
VPV	0.988	0.997	0.994	0.997
GPV	0.976	0.996	0.979	0.996

RESULTS

ICC values for inter- and intraobserver reliability of all measurements were larger than 0.75 (Table 3), indicating acceptable reliability of the upper airway measurements. All variables were normally distributed. Independent-sample *t*-tests showed that the width of the inferior limit of the glossopharynx (P3W), cross-sectional area of the anterior limit of the nasal airway (P5S), and height of the glossopharynx (GPH) in the asymmetry group were significantly larger than those in the symmetry group ($P < .05$; Table 4). A significant difference in the severity of mandibular deviation was noted between the two groups ($P < .01$; Table 4).

Pearson correlation analysis was performed to investigate the underlying correlations between the degree of mandibular deviation and upper airway parameters in the asymmetry group. For subjects with more severe mandibular deviations in subgroup II, the volume of the glossopharynx (GPV), total volume of the pharynx (TPV), length of the inferior limit of the velopharynx (P2L), and ratio of length to width of the inferior limit of the velopharynx (P2L/P2W) showed significantly negative correlations with mandibular deviation ($r > 0.7$, $P < .05$; Table 5), indicating that the greater the deviation, the narrower the velopharyngeal section. Other parameters, except the vertical distances between superior limit and inferior limit of the velopharynx (VPH), showed negative correlations with mandibular deviation, having no statistical significance (Table 5).

DISCUSSION

Previous studies have demonstrated that mandibular asymmetry may be one of the predisposing factors to airway constriction.[11] Mandibular asymmetry is commonly observed in patients with Class III malocclusion, with a proportion of up to 25%–34%.[12,13] Thus, we focused on skeletal Class III subjects with mandibular asymmetry to investigate the characteristics of the upper airway. Meanwhile, skeletal Class III patients without asymmetry served as a control to eliminate the confounding effect of the AP skeletal pattern on the upper airway.

Table 4. Descriptive Statistics and Independent Sample *T*-Tests of Symmetry and Asymmetry Groups for Upper Airway Parameters, Mandibular Deviation, and Cephalometric Measurements (N = 54)

	Symmetry (N = 28)		Asymmetry (N = 26)		
	Mean	SD	Mean	SD	*P* value
Cross-sectional linear distances					
P1L	18.57	0.59	19.37	0.65	.55
P1W	29.26	0.75	28.54	0.61	.47
P2L	16.57	1.21	17.62	1.46	.67
P2W	25.47	1.38	24.79	1.38	.82
P3L	13.80	0.98	13.68	0.92	.74
P3W	29.82	0.69	32.06	0.81	.03*
P4H	45.94	5.51	36.28	5.61	.42
P4W	29.15	2.37	29.87	2.19	.32
P5H	33.12	4.42	35.52	4.59	.10
P5W	18.64	6.54	17.03	2.50	.28
Cross-sectional area					
P1S	308.92	28.18	336.36	29.91	.70
P2S	399.84	28.85	410.07	33.72	.65
P3S	262.63	22.47	320.31	26.54	.17
P4S	149.50	70.0	119.36	71.02	.25
P5S	198.61	51.34	248.01	60.26	.01*
TPS	971.39	44.08	1066.74	49.18	.20
Cross-sectional ratio					
P1L/P1W	0.64	0.02	0.68	0.02	.27
P2L/P2W	0.67	0.04	0.72	0.04	.61
P3L/P3W	0.46	0.03	0.42	0.03	.21
Upper airway height					
NPH	21.00	0.74	19.84	0.72	.29
VPH	30.96	0.69	28.94	0.87	.09
GPH	18.39	1.29	23.59	1.23	<.01**
TPH	70.34	1.44	72.37	1.54	.34
Airway volume					
NV	12 978.02	4455.91	14799.69	3082.85	.14
NPV	7557.49	397.39	8265.60	387.59	.34
VPV	13 427.82	1175.87	14254.65	1203.46	.60
GPV	7587.70	996.54	9696.85	1277.26	.23
TPV	29 399.84	2213.68	31219.00	2229.16	.64
TV	40 536.54	15 074.88	44 817.38	13 183.61	.34
Mandibular deviation					
Deviation	1.20	0.13	7.80	0.65	<.01**
Cephalometric measurements					
ANB	−4.10	0.69	−3.50	0.60	.42
Wits	−12.9	5.8	−11.4	5.3	.55
MP-FH	28.92	1.24	30.26	1.45	.49

* $P < .05$; ** $P < .01$.

Determination of Mandibular Asymmetry

Diagnostic criteria and a threshold to separate mandibular asymmetry from symmetry subjects have not been completely determined.[21,22] Some studies used 2 mm to determine whether a subject was considered asymmetrical or not.[8] However, Haraguchi et al.[20] used a distance from symphysis menti to the sagittal plane to identify mandibular asymmetry, and reported that skeletal chin deviations of more than 4 mm were most likely judged as mandibular asymmetry. Skvarilová[23] found that an acceptable range of facial symmetry was no more than 4–5 mm. Therefore, we used 4 mm as a threshold to determine mandibular asymmetry. Subjects with a deviation less than 2 mm were classified in the symmetry group. Subjects with a distance of more than 2 mm and less than 4 mm (2 mm $\leq$ d $\leq$ 4 mm) were considered as atypical and excluded from the study.

For a better understanding of the characteristics of the upper airway in asymmetrical subjects, the asymmetry group was further divided into two subgroups according to the severity of the mandibular deviation: subgroup I included 16 subjects with mandibular deviation between 4 mm and 10 mm. The 10 subjects with a mandibular deviation over 10 mm were classified in subgroup II.

Table 5. Pearson Correlation Analyses of Upper Airway Parameters and Mandibular Deviation in Asymmetry Subgroup II (d ≧ 10 mm; N = 10)

	Deviation	
	Pearson Correlation	Sig. (2-tailed)
NPV	−0.02	0.95
P1S	−0.01	0.98
NPH	−0.09	0.80
VPV	−0.58	0.08
P2S	−0.15	0.68
VPH	0.20	0.58
GPV	−0.75	0.01*
P3S	−0.60	0.07
GPH	−0.60	0.07
TPV	−0.84	<0.01**
TPS	−0.41	0.23
TPH	−0.49	0.15
P1L	−0.15	0.68
P1W	−0.14	0.70
P2L	−0.84	<0.01**
P2W	−0.36	0.31
P3L	−0.52	0.12
P3W	−0.62	0.05
P1L/P1W	−0.09	0.81
P2L/P2W	−0.83	<0.01**
P3L/P3W	−0.23	0.52
NV	−0.22	0.33
P4S	0.06	0.80
P5S	0.19	0.40
P4H	−0.30	0.16
P4W	−0.31	0.15
P5H	−0.02	0.93
P5W	0.39	0.07
TV	−0.17	0.44

* $P < .05$; ** $P < .01$.

CBCT-Based Upper Airway Measurements

The upper airway is a 3D, irregularly shaped space, so single linear measurements as performed in conventional lateral cephalograms cannot describe upper airway morphology accurately.[24,25] Previous studies have shown that upper airway morphology could be precisely measured by CBCT with high reliability.[26] In this study, ICC values to determine inter- and intraobserver reliability were calculated for all measurements and found to be over 0.75, thus indicating acceptable reliability of upper airway measurements.

Characteristics of Upper Airway Morphology

In this study, the mean length of P2 in both groups (symmetry group 16.57 ± 1.21 mm, asymmetry group: 17.62 ± 1.46 mm) was greater than the average value in normal subjects reported by Li et al. (11.58 ± 2.48 mm),[27] confirming the effect of the sagittal skeletal pattern on upper airway morphology. The mean width of P2 was the narrowest among the pharyngeal planes, suggesting that, in the coronal plane, the morphology of the pharyngeal airway presented an hourglass form, which is narrower in the middle and wider at the ends. The cross-sectional ratios of P1, P2, and P3 (P1L/P1W, P2L/P2W, P3L/P3W) were all less than 1, indicating that the shape of the cross-sectional plane of the pharynx was elliptical, shorter anteroposteriorly and wider transversally.

The width of P3, cross-sectional area of P5, and height of the glossopharynx were significantly larger in the asymmetry group, suggesting that the anterior and inferior limits of the upper airway were significantly wider in the asymmetry group than in the symmetry group. Since no significant difference was observed between total airway volumes in the two groups, enlargement of the anterior and inferior parts of the upper airway may be a compensatory modification of the constricted airway in asymmetric subjects. Further analysis is needed to verify this assumption.

The correlation of mandibular asymmetry and upper airway morphology has seldom been studied. The current study found that, in Class III subjects with severe asymmetry (d ≥ 10 mm), the pharyngeal airway showed a tendency toward greater constriction with increasing severity of mandibular deviation. The anterior and inferior limits of the upper airway in symmetry subjects were significantly larger than those in asymmetry subjects, possibly as a compensatory effect. From a clinical standpoint, the current results could be helpful for an orthognathic surgeon when making treatment plans for Class III patients with severe mandibular prognathism. Some investigations showed that a mandibular setback might significantly narrow the airway space.[7–9] Mandibular asymmetry is commonly observed in patients with severe Class III prognathism, and the current results suggest that the pharyngeal airway tends to become constricted and more elliptical as mandibular deviation increases in Class III subjects ($P < .01$). Therefore, in skeletal Class III subjects with mandibular asymmetry, the influence on airway dimensions after surgical correction of the AP discrepancy should be taken into consideration and maxillary advancement or another technique might be considered as part of the treatment strategy.[28]

CONCLUSIONS

- The width of P3, cross-sectional area of P5, and height of the glossopharynx in asymmetrical subjects were significantly larger than those in the symmetry group of skeletal Class III malocclusion patients ($P <$ .05).
- The pharyngeal airway showed a tendency to be more constricted and more elliptical as d became more severe in Class III subjects ($P < .01$)

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