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Three-dimensional evaluation of upper airway in patients with different anteroposterior skeletal patterns

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Structured Abstract

Objectives – To investigate variability in the upper airway of subjects with different anteroposterior skeletal patterns by evaluating the volume and the most constricted cross-sectional area of the pharyngeal airway and defining correlations between the different variables.

Material and methods – The study sample consisted of 60 patients (29 boys, 31 girls) divided into three groups: Class I (1 ≤ ANB≤3), Class II (ANB>3), and Class III (ANB<1), to evaluate how the jaw relationship affects the airway volume and the most constricted cross-sectional area (Min-CSA). Differences between groups were determined using the Tukey–Kramer test. Correlations between variables were tested using Pearson's correlation coefficient.

Results – The volume and the Min-CSA of the pharyngeal airway (PA) were significantly related to anteroposterior skeletal patterns ($p < 0.05$). The nasopharyngeal airway (NA) volume of Class I and Class III subjects was significantly larger than that of Class II subjects ($p < 0.05$). The Min-CSA and the length of PA were significantly related to the volume of PA ($p < 0.05$). The site and the size of the Min-CSA varied among the three groups.

Conclusions – The volume and the most constricted cross-sectional area of the airway varied with different anteroposterior skeletal patterns. The NA volume of Class I and Class III subjects was significantly larger than that of patients with a Class II skeletal pattern.

Key words: cephalometry; cone-beam CT; measurement; tomography; upper airway

Introduction

The relationship between craniofacial morphology and respiratory function has been the focus of investigation since the late 19th century (1). Previous studies have demonstrated the mutual interaction between the developmental pattern of the face and the pharyngeal airway. The influence of airway obstruction on nasal respiratory function can cause changes in breathing pattern, which result in anomalies of craniofacial growth and dental position (2–5). Many reports have suggested a relationship between various malocclusion patterns and variations in the size and form of the oropharyngeal airway caused by the palate and/or tongue position (6, 7). Others have concluded that malocclusion is a predisposing factor in airway morphological changes and respiratory problems, while a small, retroposed mandible, enlarged tongue and soft palate, inferiorly positioned hyoid bone, and retroposed maxilla are suggested to be predisposing factors for obstruction of the pharyngeal airways (8–10).

Despite extensive research into airway anatomic factors and craniofacial morphology, the complex shape of the airway is not represented well with two-dimensional images. Recently, cone-beam computed tomography (CBCT) has been used to provide three-dimensional images, which makes it possible to visualize various sites of interest from different perspectives and internal anatomic structures independently. It can also assess upper airway cross-sectional area and volume precisely with an accessible, low-radiation, cheap, rapid, and non-invasive scan (11–14).

The most constricted cross-sectional area (Min-CSA) of the pharynx airway is adopted as the most common measurement for evaluating airway morphology and potential risks of OSA. To report the location of the most constricted place in the airway, most researchers use the retropalatal (RP) and retroglossal (RG) regions on the midsagittal slice as intraoral landmarks (15–17). However, these landmarks are based on 2D measurement and, in many cases, are not the most constricted cross-sectional area of the airway. This study has used 3D measurements to detect the most constricted cross-sectional area, which will result in more precise assessment of the airway morphology. The same measurement has been used to compare the static morphology of the upper airway in OSA patients and healthy controls (18, 19), but has not been applied to the study of normal nasorespiratory patients with different dentofacial skeletal patterns.

The aims of this study were to investigate variability in upper airway morphology and anatomy in subjects with different anteroposterior skeletal patterns by evaluating the volume and the most constricted cross-sectional area of the pharyngeal airway and identifying any correlation between the different variables.

Material and methods

The study protocol was approved by the Ethics Review Committee at dental hospital, Showa University. A consent form allowing the use of their orthodontic records was signed by each subject participating in the study, all of whom were sourced from the patient database of the Department of Orthodontics (age: 14–18 years). Inclusion criteria required that subjects have a complete dentition and a symmetric mandible. When CBCT is taken, the Frankfort horizontal (FH) plane should be parallel to the floor (Fig. 1). Exclusion criteria included a body mass index (BMI) higher than 28, congenital craniofacial deformities, nasal obstruction, history of snoring, obstructive sleep apnea, detectable airway pathology, and history of orofacial surgery or orthodontic treatment.

The study sample included 60 patients (mean age: 15.65 ± 1.39) who could meet the above inclusion criteria. Anteroposterior skeletal patterns were established initially from visual inspection of dentofacial photographs and a lateral cephalometric radiograph and confirmed by their ANB angles (Class I: $1 \leq$ ANB≤ 3; Class II: ANB>3; Class III: ANB<1). Their age, gender, and distribution by ANB angles are shown in Table 1.

Each subject was seated in a chair with his or her Frankfort horizontal (FH) plane parallel to

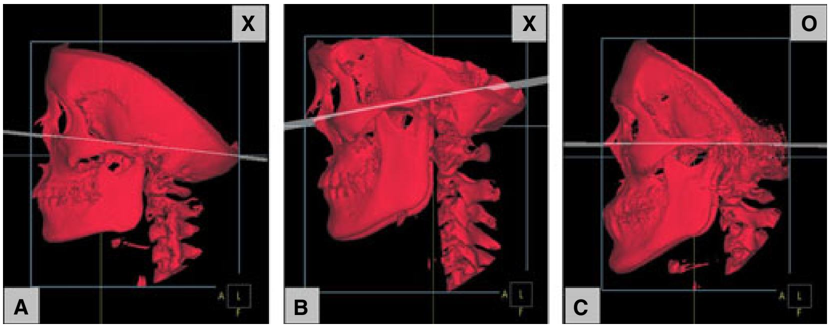

Fig. 1. Determination of the Frankfort horizontal plane parallel to the floor as the horizontal reference line for 3D measurement. (A, B) Image would be excluded (X) due to non-horizontal Frankfort plane; (C) Frankfort plane is horizontal, so image would be accepted (O).

Table 1. **Sample characteristics**

	Class I		Class II		Class III		
	Male	Female	Male	Female	Male	Female	Total
Subject (n)	10	10	8	12	11	9	60
Age (year) (mean ± SD)	15.20 ± 1.03	15.30 ± 1.34	15.25 ± 1.58	15.25 ± 1.58	16.73 ± 0.91	16.11 ± 1.36	15.65 ± 1.39
Range (year)	14–17	14–18	14–18	14–18	15–18	14–18	14–18

the floor. A CBCT device (CB MercuRay, Hitachi Medical, Tokyo, Japan) was set to 110 kV/10 mA with an exposure time of 10 s. Patients were asked to bite with maximum intercuspation and their lips and tongue in the resting position, and not to swallow, breathe, or move their head or tongue during image capture. Each 3D image consisted of 512 slices, with a slice thickness of 0.38 mm. Data were stored in Digital Imaging and Communications in Medicine (DICOM) format and imported into the CBWorks software (CBWorks 2.1, CyberMed Corp, Seoul, Korea) for further processing and analysis.

To identify the relevant pharynx airway volumes using the CBWorks software, the threshold was set to a range between −1024 and −318 Hounsfield units. Each patient was initially evaluated using horizontal, sagittal, and coronal images. An approximately square-shaped prism was first defined to outline the general area.

For the nasopharyngeal airway (NA) volume (Vol-NA), the border of NA was shown in Fig. 2. In terms of the oropharyngeal airway (OA) volume (Vol-OA), the hypopharyngeal airway (HA) volume (Vol-HA), and the pharyngeal airway (PA) volume, the borders were shown in Fig. 3. After determination of the borders, the vertical lengths of the OA (L-OA) and HA (L-HA) were measured and recorded on the midsagittal slice (Fig. 3A, B). The length of the PA (L-PA), defined as the sum of L-OA and L-HA, also served as a quantitative index of the hyoid bone position (Fig. 3C). For the intraoral airway (IO) volume (Vol-IO), we used the volume of the oral cavity air space between the palate and the tongue as a quantitative index of tongue position (15). After determination of the volumes of interest, we used the region of interest editing tool function and the volume of interest editing tool to eliminate the most undesired hollow structures. Then, the object was threshold-segmented and slice-edited by hand to remove any visible extraneous scatter, artifacts or background, similar to the method described by Meehan (20). Once segmentation was performed, the software automatically computed pharyngeal airway volumes in cubic millimeters. After segmentation, the resulting set of masks (highlighted areas representing each structure of interest within each slice of the CBCT scan) was rendered into a shaded surface

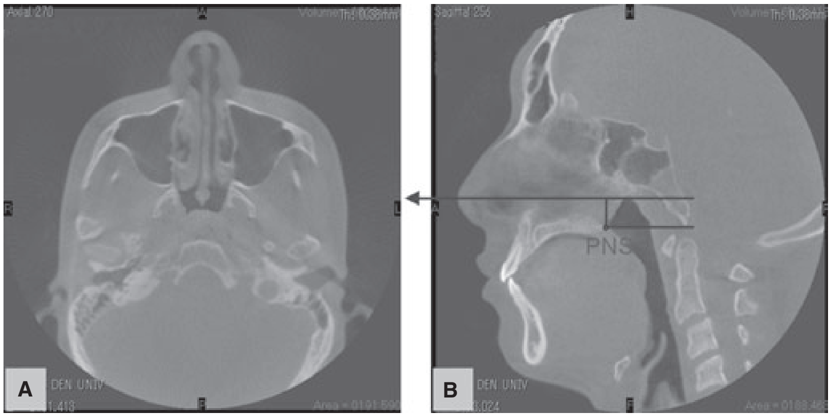

Fig. 2. The border of the NA. (A) Axial view. The last slice before the nasal septum fuses with the posterior wall of the pharynx; (B) sagittal view, showing reflection of the axial slice and the superior borders of the NA airway volume. The inferior limit of the NA airway was defined as the axial plane parallel to the FH plane passing through PNS; the anterior limit was defined as the posterior nasal plane (Pna), a frontal plane perpendicular to the FH plane passing through the posterior nasal spine (PNS).

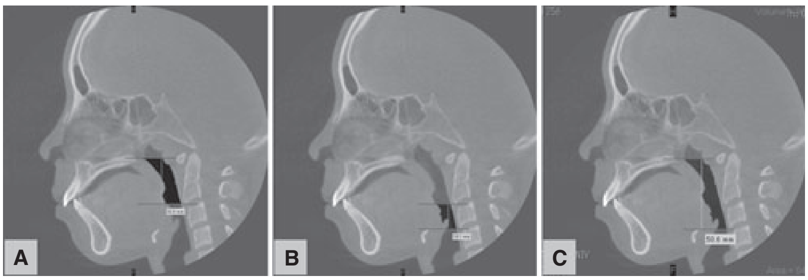

Fig. 3. (A) Midsagittal plane showing oropharyngeal airway (OA) volume. The superior border was defined as the horizontal line through the posterior nasal spine (PNS). The inferior border was defined as the horizontal line passing from the most anteroinferior point of the second cervical vertebrae. (B) Hypopharyngeal airway (HA) volume. The inferior limit of the OA was defined as the superior limit of the HA. The inferior limit of the HA was defined as the horizontal line coming into contact with the most superior margin of the body of the hyoid bone. (C) Pharyngeal airway (PA) volume. The PA volume was defined as the sum of the OA and HA volumes.

mesh in the CBWork's SSD tool. Parameters were set at high quality and unconstrained smoothing at a critical angle of 120°(21).

The cross-sectional area (in square millimeters) is automatically displayed on the axial image by the software. The user can scroll through all cross-sectional images and determine the most constricted cross-sectional area (Min-CSA) of the PA. After the location of Min-CSA was decided, its vertical length (L-CSA) was measured with linear measurement tools and defined as the distance between the Min-CSA and the upper border of OP in the mid-sagittal view (Fig. 4B).

Statistical analysis

SPSS 11.5 software (SPSS Inc., Chicago, IL, USA) was used for all statistical analyses. In each group, means and standard deviations were determined for age, gender, skeletal variables, and for volumetric, area, and linear measurements of the airway regions. We tested for the normality of the distributions, with an alpha value of 0.05 being accepted as the significance level. A Tukey–Kramer multiple comparison test was performed among Class I, II, and III malocclusions. Pearson's correlation coefficient test was performed to identify any significant relationships between the PA and craniofacial morphology.

Results

To assess the reliability of the measurements, lateral cephalometric variables and airway

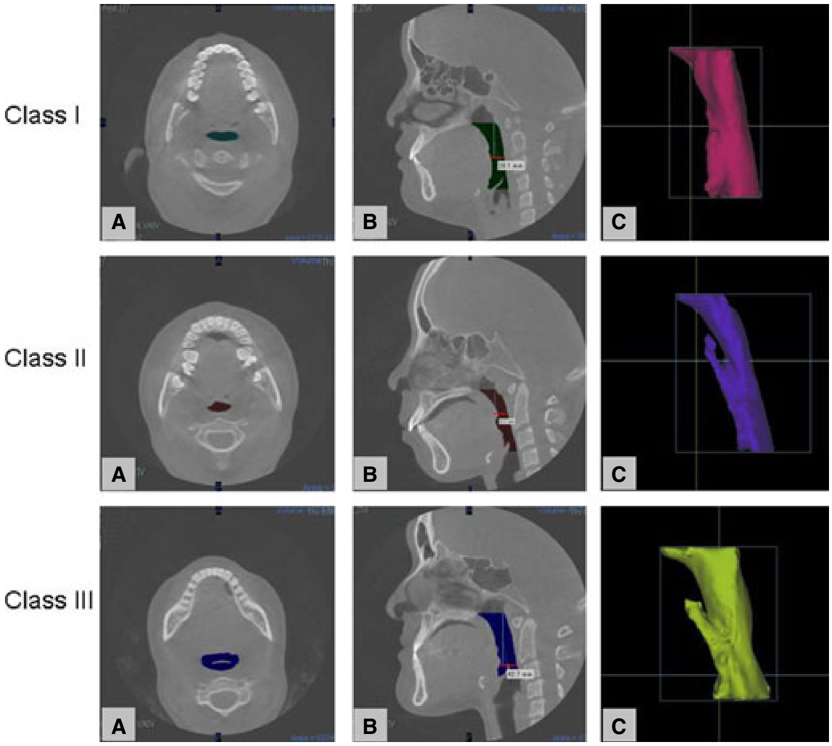

Fig. 4. The most constricted cross-sectional area in patients with different skeletal patterns. (A) Axial plane showing the Min-CSA. (B) Midsagittal plane showing the L-CSA. (C) SSD image showing the position of Min-CSA, as indicated by the location of the horizontal 3D cursor.

dimensions of 15 randomly selected CT scans were remeasured by the same operator a week after the first measurements. A paired t-test detected no statistically significant differences (22). Random error was estimated using Dahlberg's double determination method (23). Random errors varied from 0.37 to 2.19 mm in linear measurements, from 9.16 to 33.28 mm^2 in area measurements, and from 91.53–152.82 mm^3 in volume measurements.

Means and standard deviations for cephalometric, cross-sectional, and volumetric variables were compared by gender. Because no gender differences were found in any measurement, subjects were combined for subsequent analyses.

Table 2 shows cephalometric variables for different groups. There were statistically significant differences between the groups for the ANB, probably because of the different skeletal features of each group. As for SNB, there were significant differences between Class II and III groups, but there were no significant differences in the FMA between groups.

Table 3 shows the means and standard deviations of variables for different groups. Statistically significant differences existed among the different groups ($p < 0.05$); the comparison results are also shown in Table 3. The Vol-NA values in the Class I and III groups were significantly higher than that in the Class II group, whereas there was no significant difference between Class I and Class III groups. There were also significant differences between the groups in terms of Vol-OA, Vol-HA, and Vol-PA values. The highest and lowest volumes were in the Class III and Class II groups, respectively. The Vol-IO values were highest in the Class III group; there was no significant difference between the Class I and Class II groups. Values of L-OA, L-HA and L-PA were not significantly different between Class I and Class II, but the airway of the Class III group was significantly longer than that of Class I. Moreover, compared with Class II, Class III had larger Vol-OA and Vol-HA values, although these differences were not significant. However, the Vol-PA (the sum of Vol-OA and Vol-HA) was significantly larger in Class III than in Class II. Class III subjects also had the largest Min-CSA and L-CSA. Moreover, the mean of L-CSA was bigger than that of L-OP, closer to the L-PA than to the L-OP, and was usually

Table 2. **Descriptive statistics showing cephalometric variables according to the ANB angle**

	SNA (°)	SNB (°)	ANB (°)	FMA (°)
Class I (n = 20)				
Mean ± SD	80.5 ± 5.3	78.6 ± 5.4	1.9 ± 0.5	29.4 ± 5.3
Min	75.2	74.2	1.0	15.9
Max	92.8	91.2	3.0	42.8
Class II (n = 20)				
Mean ± SD	83.0 ± 3.2	78.1 ± 3.0	4.96 ± 1.5	29.1 ± 5.6
Min	78.2	74.1	3.4	17.98
Max	88.7	83.9	7.8	37.93
Class III (n = 20)				
Mean ± SD	80.6 ± 2.4	84.3 ± 1.9	−3.7 ± 1.2	30.4 ± 5.0
Min	75.6	79.8	−6.6	17.6
Max	82.4	85.7	−2.1	37.7

Table 3. **Descriptive statistics showing means and standard deviations of volumetric, length, and cross-sectional variables, and comparison of these measurements according to anteroposterior skeletal patterns**

	Class I (n = 20)	Class II (n = 20)	Class III (n = 20)	Class I–Class II	Class I–Class III	Class II–Class III
Vol–NA (mm^3)						
Mean ± SD	5444.5 ± 1089.2	4054.2 ± 1196.1	6053.5 ± 1148.5	**	n.s.	**
Vol–OA (mm^3)						
Mean ± SD	8673.7 ± 2707.3	5207.5 ± 1662.1	12505.6 ± 2403.9	**	**	**
Vol–HA (mm^3)						
Mean ± SD	5003.1 ± 2394.2	3334.4 ± 1982.9	6885.7 ± 1538.6	*	*	**
Vol–PA (mm^3)						
Mean ± SD	13676.7 ± 3304.3	8541.9 ± 2628.1	19391.3 ± 3385.9	**	**	**
Vol–IO (mm^3)						
Mean ± SD	1100.1 ± 1020.7	812.1 ± 1164.3	3638.8 ± 3127.2	n.s.	**	**
L–OA (mm)						
Mean ± SD	29.1 ± 4.1	31.9 ± 4.0	34.8 ± 5.3	n.s.	*	n.s.
L–HA (mm)						
Mean ± SD	19.4 ± 5.4	20.1 ± 4.9	23.4.6 ± 3.4	n.s.	*	n.s.
L–PA (mm)						
Mean ± SD	48.5 ± 5.6	51.9 ± 6.5	58.3 ± 6.4	n.s.	**	**
L–CSA (mm)						
Mean ± SD	26.8 ± 5.3	19.7 ± 3.8	45.7 ± 5.3	**	**	**
Min–CSA (mm^2)						
Mean ± SD	235.9 ± 89.8	160.3 ± 46.7	331.5 ± 58.8	**	**	**

*$p < 0.05$; **$p < 0.01$; n.s., not significant.

positioned in the lower hypopharyngeal region. Class II subjects had the smallest Min-CSA, and the mean of L-CSA was smaller than that of L-OP and was usually positioned in the retropalatal region. As for Class I subjects, the Min-CSA was larger than that of Class II subjects and

Table 4. **Pearson's correlation coefficients for airway volumes compared with the variables used in this study**

	Vol–NA	Vol–OA	Vol–HA	Vol–PA	Vol–IO
Vol–NA	1	n.s.	n.s.	n.s.	n.s.
Vol–OA	n.s.	1	**	**	n.s.
Vol–HA	n.s.	**	1	**	**
Vol–PA	n.s.	**	**	1	*
Vol–IO	n.s.	n.s.	**	*	1
L–OA	n.s.	**	n.s.	n.s.	n.s.
L–HA	n.s.	*	**	**	**
L–PA	n.s.	**	**	**	**
L–CSA	n.s.	**	n.s.	**	n.s.
Min–CSA	n.s.	**	**	**	n.s.
SNA	n.s.	n.s.	n.s.	n.s.	n.s.
SNB	n.s.	**	**	**	n.s.
ANB	*	(−)**	(−)**	(−)**	(−)*
FMA	n.s.	n.s.	n.s.	n.s.	n.s.

*$p < 0.05$; **$p < 0.01$; n.s., not significant; (−), negative correlation.

smaller than that of Class III subjects, with the mean of L-CSA close to that of L-OP, and it tended to be positioned in the lower oropharyngeal or upper hypopharyngeal region.

Table 4 shows the correlation between different parts of the airway, and between airway volumes and other variables. Vol-NA values had no correlation with the Vol-PA and pharyngeal cross-sectional area. However, a positive correlation was found between Vol-OA, Vol-HA, and Vol-PA. L-OA was only correlated with Vol-OA, whereas L-HA was not only correlated with Vol-HA, but also with Vol-OA, Vol-PA and Vol-IO. Moreover, Min-CSA and SNB showed positive correlations with all pharyngeal airway volumes except Vol-NA and Vol-IO, whereas the ANB showed negative correlations with all volumetric measurements except Vol-NA.

Discussion

The present study of the pharyngeal airway uses CBCT to generate 3D anatomic images, which enable the precise measurement of the most constricted cross-sectional area and volumes of the airway. Compared with conventional measurements, CBCT can better assess the cross-sectional dimensions of the airway space and greatly reduce operator-dependent bias by computerizing the drawing of airway circumferences and calculation of cross-sectional areas (24).

Regarding patient positioning, many studies have reported that the size and shape of the airway are influenced by head posture (2, 25, 26). In the present study, the CBCT images were acquired with the patients in an upright position, which is typical for most CBCT machines. Studies have documented that images recorded in the upright position are adequate to evaluate the airway (27). In this study, the FH plane was set parallel to the floor and checked by 3D measurement to minimize differences in airway size arising from changes in head posture (28). Lowe et al. (29) reported that airway dimensions can change according to the respiration phase. In our study, the acquisition time for our scanner was 10 s, a sufficiently short period that the patient can hold their breath to control for possible airway changes. That practice might have kept the airway constant, but it also might have promoted large inspirations followed by breath holding. Therefore, further research is needed to present the change in the airway movement during each breath and define airway resistance and airflow (13).

Previous studies have suggested that the quiescent period for pharyngeal structural development is most likely to lie between 14 and 18 years (17). The pharyngeal structures continue to grow rapidly until 13 years of age (30), then enter a quiescent phase before a second phase of development between 20 and 50 years of age during which the soft palate thickens and lengthens, and the pharyngeal region narrows (31, 32). Recently, Chiang et al. (33) have provided adequate information about how the airway grows; whereas the length of the airway seems to stop developing for the female of the age range, the males continue to develop at the same stage. To make a comparison between the similar researches, the age range in the present study was chosen with the age from 14 to 18.

The clinical significance and reliability of the ANB angle as a means of classifying different anteroposterior skeletal patterns has been the subject of much debate. It is nevertheless the most commonly used cephalometric measurement for evaluation of skeletal patterns (15–17). Ishikawa et al. (34) reported that the ANB angle gives high accuracy predictions for jaw relationships in post-pubertal subjects. In our study, the photographs and clinical recordings were combined with the ANB angle to determine the jaw relationship.

In this study, no significant gender difference was found for any of the cross-sectional and volumetric measurements, in agreement with the findings of Hakan (17) and Oh (35). However, Alves et al. (30) found a significant gender-related difference in Vol-OA for the retropalatal and retroglossal regions in the Class III group, but no significant difference was observed for the nasal cavity volume. The use of different anatomic landmarks to define the airway may account for the apparent contradiction with our own results. Chiang et al. (33) also found that males have longer and larger volumes of the airway. Different sample size and age distribution might be the reasons of gender difference in the volume and shape of airway.

We have observed that Class I and Class III subjects had significantly larger NA volumes compared with Class II subjects, which agrees with the findings of Haken (17). In a 3D study, Kim et al. (16) found that the NA volumes of Class I subjects were greater than those of Class II subjects, although not significantly. In addition, the present study also suggested that there were no significant correlations between the volumes of NA and other airway structures, consistent with the research of Kim. Moreover, Kim et al. found that, located above the hard palate, the anterior and posterior parts of the NA volume separated by the Pna plane were positively correlated. However, Linder-Aronson (36) studied the relationship between the upper and lower parts of the airway and reported that a smaller nasopharyngeal airway was accompanied by a larger oropharyngeal airway. These contrary findings might be attributable to the 2D measurement used in the latter study.

We also show that values of Vol-PA (including Vol-OA and Vol-HA) and Min-CSA were negatively correlated with the ANB angle (Class III>-Class I>Class II) and positively correlated with the SNB angle. Hakan et al. (17) also found that Class I and Class III subjects had significantly larger airway volumes compared with Class II subjects, but they found no significant difference between Class I and Class III groups. These different results may be due to the Class III patients in our study having more protruding lower jaw position than those in the previous study. Kim et al. (16) also found volumetric measurements of the airway significantly correlating with the ANB angle and stated that retrognathic patients tended to have a smaller airway volume compared with patients with a normal anteroposterior skeletal relationship. Conversely, Watson et al. (37) concluded that anteroposterior pharyngeal airway dimensions were not affected by changes in the ANB angle. Because these previous studies were based on lateral cephalograms, more 3D studies are needed to clarify these conflicting results. Moreover, future studies need to address further details on mandibular and maxillary position related to the airway (38).

Our results showed a high correlation between Vol-PA and Min-CSA. The most constricted site of the PA varied with different anteroposterior skeletal patterns (Fig. 4). Class II patients had the smallest mean Min-CSA (160.3 ± 46.7 mm^2), which was usually in the upper oropharyngeal region, whereas for Class III patients the mean Min-CSA was generally the largest among the three skeletal patterns (331.5 ± 58.8 mm^2) and was generally found to be in the lower hypopharyngeal region. For Class I patients, the most constricted site tended to be in the lower oropharynx or upper hypopharynx. The above analysis indicates that the site of the Min-CSA varies in the upper airway among the three groups. Chiang et al. (33) has also reported that the site of Min-CSA can occur at almost any level of the airway, but particularly at the oropharynx and hypopharynx. Tso et al. (21) reported that according to their research on 10 Class I subjects, the most constricted site varies as to its location in the pharynx airway but primarily in the oropharynx. In Class II patients, relatively short and/or posteriorly placed mandibles might force the soft palate back into the pharyngeal space, causing a reduction in Vol-OA and a constricted cross-section around the soft palate. Conversely, for Class III patients, relatively long and/or anteriorly placed mandibles might force the tongue to move anteriorly, causing a wide Min-CSA located in the HP region. Based on this result, locating the most constricted site in the PA is of great clinical significance in understanding the size and volume of the pharyngeal airway and for diagnosis and treatment planning.

Furthermore, as tongue position is of great clinical interest due to its important role in maintaining the upper airway dimensions (39), our study also addresses the relationship between tongue position and other airway variables. The Class III group had significantly greater IO volumes and L-PA than Class I or Class II, indicating that a low tongue position is a characteristic of Class III patients. Pae et al. (40) reported that as the position of the hyoid bone moves inferiorly, the pharyngeal length increases because the hyoid bone and epiglottis are in a close anatomic relationship. Our results suggested that the L-OA was positively correlated only with Vol-OA, whereas the L-HA and L-PA were positively correlated with the volume of PA and IO. This might indicate that the hyoid bone position is closely related with airway volumes, especially in Class III patients.

In summary, volumetric studies with CBCT provide a new perspective to the study of the airway and its relation to different skeletal patterns by precisely assessing the most constricted cross-sectional area, analyzing in detail the volume and shape of the airway and making cephalometric evaluations that might benefit orthodontic diagnosis and treatment planning.

Conclusions

The volume and the most constricted cross-sectional area of the airway vary with different anteroposterior skeletal patterns. The NA volume of Class I and Class III subjects was statistically significantly bigger than that of Class II. Detailed analysis and precise assessment of the volume and shape of the airway along with cephalometric evaluations might prove to be a valuable diagnostic addition in orthodontics.

Clinical relevance

Compared with previous studies with conventional 2D measurements, this study used a 3D evaluation of the airway provided by CBCT to better assess the volumetric dimensions and cross-sectional area of the airway. These findings have a significant impact on the assessment of upper airway and its relation to different skeletal patterns, analyzing in detail the volume and the shape of the airway and their relation to the most constricted area of the airway, making cephalometric evaluations that might benefit orthodontic diagnosis and treatment planning.

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