An airway study of different maxillary and mandibular sagittal positions

Hakan El* and Juan Martin Palomo**

*Department of Orthodontics, Faculty of Dentistry, Hacettepe University, Ankara, Turkey and **Department of Orthodontics, School of Dental Medicine, Case Western Reserve University, Cleveland, OH, USA

Correspondence to: Juan Martin Palomo, Department of Orthodontics, School of Dental Medicine, Case Western Reserve University, 10900 Euclid Avenue, Cleveland, OH 44106, USA. E-mail: palomo@case.edu

SUMMARY   The aim of this study was to evaluate the oropharyngeal (OP) and nasal passage (NP) volumes along with various airway variables of patients with normal nasorespiratory functions having different dentofacial skeletal patterns and to evaluate the correlations between different variables and the airway. One hundred and one patients (57 males and 44 females, aged 14–18 years) having pre-treatment cone beam computed tomography images and complete medical records were selected. The patients were divided into five groups as Class I (CI, $81 \geq SNA \geq 77$; $80 \geq SNB \geq 76$; $3 \geq ANB \geq 1$), Class II maxillary protrusion (CIIMaxP, $SNA > 81$; $80 \geq SNB \geq 76$; $ANB > 3$), Class II mandibular retrusion (CIIMandR, $81 \geq SNA \geq 77$; $SNB < 76$; $ANB > 3$), Class III maxillary retrusion (CIIIMaxR, $SNA < 77$; $80 \geq SNB \geq 76$; $ANB < 1$), and Class III mandibular protrusion (CIIIMandP, $81 \geq SNA \geq 77$; $SNB > 80$; $ANB < 1$). Posterior airway space, area of the most constricted region at the base of the tongue (minAx), and OP volume were significantly higher for the CIIIMandP group, whereas CIIMandR subjects had the lowest values. The only significant difference for the NP volume was between CI and CIIMandR groups where a smaller volume for the CIIMandR group was observed. The minAx was the variable that presented the best correlation with the OP airway volume. It seems that a detailed analysis of airway may prove to be a valuable diagnostic addition in orthodontics.

Introduction

The relationship between craniofacial morphology and respiratory function has been studied extensively since the beginning of 20th century (Angle, 1907). Some authors claim that patients with deficient respiratory functions present with lip incompetency, increased anterior face height, maxillary constriction, protruded maxillary incisors with Class II molar relationship, open bite, and narrow external nares, so called 'adenoid facies' (Ricketts, 1968; Linder-Aronson, 1970; Moore, 1972). However, there is still a dispute whether this relationship between craniofacial morphology and respiratory function causes dentofacial anomalies (Gwynne-Evans, 1958; Leech, 1958; Kluemper *et al.*, 1995). Although there is still a discussion on this topic today, it is a general belief that the upper airway structures play a significant role over the development of craniofacial complex (Tourne, 1991; Johnston and Richardson, 1999; Martin *et al.*, 2006).

It is incorrect to relate skeletal and dental malocclusions only to airway pathologies. Studies have been conducted on subjects with various skeletal conditions having no upper airway diseases. Ceylan and Oktay (1995) investigated pharyngeal size on lateral cephalometric head films of 45 males and 45 females and they found that the oropharynx areas of patients with ANB <1 degree were larger compared to subjects with ANB >5 degrees. Kirjavainen and

Kirjavainen (2007) studied the upper airway of 40 patients with Class II division 1 malocclusion and compared them to 80 children with a Class I molar relationship. They concluded that the children with Class II malocclusion had a wider or similar nasopharynx than the controls but narrower oropharyngeal (OP) and hypopharyngeal areas. Martin *et al.* (2011) also found that the lower pharyngeal dimensions were increased in Class III subjects. Similar findings were noted in the studies of Trotman *et al.* (1997) and Athanasiou *et al.* (1994). All the mentioned studies were conducted using lateral cephalograms.

Contemporarily, the lateral cephalogram still seems to be the dominating evaluation tool in the field of upper airway research in spite of its disadvantages. The main disadvantage, without any doubt, is considered as the degradation of a three-dimensional (3D) entity into two dimensions (Lenza *et al.*, 2010). With the introduction of computed tomography (CT), shortcomings of lateral cephalograms have been prevented. Despite the widespread use of CT examinations in clinical practice, this new technology brought along concerns about the exposure to ionizing radiation and its potential hazards. Therefore, radiation dose and strategies for dose reduction, especially for younger patients, have become an important focus of interest. With the advent of cone beam CT (CBCT), lower radiation doses and faster image acquisition times has become possible (Ludlow and

Ivanovic, 2008; Palomo *et al*., 2008; Mah *et al*., 2010). Although CT technology is a hard tissue-oriented imaging tool, with the use of DICOM (Digital Imaging and Communications in Medicine) viewer programs, hollow structures such as the airway can also be visualized in 3D. Therefore, a whole new set of possibilities in the area of airway research has opened (Alves *et al*., 2008; Grauer *et al*., 2009; Kim *et al*., 2010). In a previous study by the same authors (El and Palomo, 2011) the relationship between different dentofacial skeletal patterns and airway volume was evaluated, investigating a sample of Class I, II, and III subjects. However, none of these studies evaluated the airway volume according to jaw-specific skeletal relationship.

The aim of the current study is to evaluate the OP and nasal passage (NP) volumes of patients with normal nasorespiratory functions having different dentofacial skeletal patterns and to evaluate the correlations between different variables and the airway.

Materials and methods

The experimental protocol used in this study was approved by the Case Western Reserve University, University Institutional Review Board. All the patients used in this study were obtained from the digital patient database of the Department of Orthodontics, Case Western Reserve University. Using the Ortho II ViewPoint software (Ortho II Computers Systems, Ames, Iowa, USA), 101 patients (57 males and 44 females, aged 14–18 years) having pre-treatment CBCT images and complete medical records were selected. Each patient had a signed consent form allowing the use of orthodontic records. Age was not statistically significantly different between the genders ($P = 0.451$). Exclusion criteria included transverse deficiencies, severe hypodivergent growth pattern (FMA <19 degrees), severe hyperdivergent growth pattern (FMA >31 degrees), obese subjects according to their body mass index (BMI $\geq$ 30), congenital craniofacial deformities, detectable pharyngeal pathology through inspection of the images, nasal obstruction, history of mouth breathing, snoring, obstructive sleep apnoea, history of adenoidectomy, and scans showing incomplete imaging of the airway. In order to eliminate cephalometric variability, only the self-reported caucasian subjects were included in this study.

All the CBCT images used were previously taken for orthodontic reasons and were only taken after a clinical examination and the decision by the treating doctor that a CBCT would further help in the patient's diagnosis or treatment planning. When a CBCT was taken, the As Low As Reasonably Achievable principle was followed, including the use of one of the lowest doses available in the market (2 mA). No patient was contacted or CBCT taken for the purpose of our study. Our objective was to use existing data in order to help diminish the gap in knowledge when relating airway and sagittal skeletal position. All CBCTs were acquired using a modified Hitachi CB Mercuray™ (Hitachi Medical Systems America Inc., Twinsburg, Ohio,

USA) CBCT device. The Hitachi CB MercuRay scanner used was modified in order to provide lower radiation exposure while maintaining the diagnostic image quality. All the images were taken at the custom low dosage of 2 mA, 120 kVp, and a 12 inch field of view setting (F Mode). Each patient's image data consisted of 512 slices, with a slice thickness of 1 mm and a resolution of 1024 × 1024 pixels and 12 bits per pixel (4096 gray scale). The reconstruction volume size was 150 × 150 mm, with the voxel size of 0.293 × 0.293 mm. The images were taken in the sitting position with patient's head in the natural head posture, teeth in maximum intercuspation position, and at the end of exhalation period when the patient was not swallowing. A lead apron protecting the chest and lower part of the neck was worn by the patient at all times during the scanning procedure.

Antero-posterior skeletal relationship was determined using the lateral cephalometric films generated from 3D CBCT scans using the Dolphin Imaging program (Dolphin Imaging & Management Solutions, Chatsworth, California, USA). In order to determine the skeletal pattern, ANB, SNA, and SNB angles and CoGn and CoA linear measurements were calculated by a single experienced operator (H.E.; Figure 1). The patients were divided into five groups as Class I (CI, 81 $\geq$ SNA $\geq$ 77; 80 $\geq$ SNB $\geq$ 76; 3 $\geq$ ANB $\geq$ 1), Class II maxillary protrusion with normal positioned mandible (CIIMaxP, SNA > 81; 80 $\geq$ SNB $\geq$ 76; ANB > 3), Class II mandibular retrusion with normal positioned maxilla (CIIMandR, 81 $\geq$ SNA $\geq$ 77; SNB < 76; ANB > 3), Class III maxillary retrusion with normal positioned mandible (CIIIMaxR, SNA < 77; 80 $\geq$ SNB $\geq$ 76; ANB < 1), and Class III mandibular protrusion with normal positioned maxilla (CIIIMandP, 81 $\geq$ SNA $\geq$ 77; SNB > 80; ANB < 1). Midface length (CoA) and effective mandibular length (CoGn) were also taken into account while forming the groups (McNamara, 1984).

The InVivoDental 5.0 (Anatomage Inc., San Jose, California, USA; IVD) program was used to render the OP and NP volumes, separately. The superior limit of the
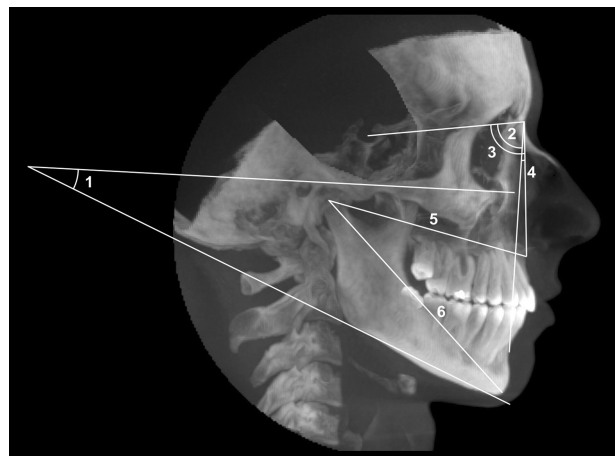

Figure 1 Angular and linear measurements. (1) FMA angle, (2) SNB angle, (3) SNA angle, (4) ANB angle, (5) CoA—midface length, (6) CoGn—effective mandibular length.

OP airway was determined to be the line passing from the palatal plane (ANS–PNS) and extending to the posterior wall of the pharynx, whereas the inferior limit was decided as the line that is parallel to the palatal plane and passing from the most antero-inferior point on the second cervical vertebrae. In order to define the superior limit of the NP airway volume, the last slice before the nasal septum fuses with the posterior wall of the pharynx was used. For this purpose, the aforementioned slice was found on the axial view first and then reflected to the sagittal slice. The inferior limit was determined to be the superior limit of the OP airway volume (Figure 2). In addition to these volumetric measurements, the vertical length of the OP airway (between the limits of the OP airway volume) and the posterior airway space (PAS; the most constricted space behind the base of the tongue and limited by soft tissues) were measured on the midsagittal slice (Figure 2) for comparative purposes. Also, the sagittal line corresponding to the PAS region was opened on the axial slice and the area of the most constricted region at the base of the tongue (minAx) was calculated (Figure 2). IVD program was also used for the area and length measurements. All data were collected by a single experienced operator (XX).

SPSS Statistics 17.0 (SPSS Inc., Chicago, Illinois, USA) program was used for all statistical analysis. Kolmogorov—Smirnov test was used to check the normality of the data. Due to the non-normality of the distribution of most of the airway variables, non-parametric tests were used.

Differences between the groups were determined using Kruskal–Wallis test. In cases where Kruskal–Wallis test was found significant, further pairwise comparisons were done using the Mann–Whitney U-test with Bonferroni correction. Spearman's rank correlation coefficient was used to assess the correlations between airway and skeletal variables. All measurements were repeated for 30 randomly selected subjects in order to test for reliability, using the intra-class correlation coefficient (ICC) for volumes and the Dahlberg's formula ($\sqrt{\dfrac{\sum d^2}{2n}}$) for linear, areal, and angular measurements (Dahlberg, 1949). The statistical significance was set at 0.05.

Results

Reliability results showed an error of 0.58 mm, 3.60 mm^2, and 0.50 degrees for linear, areal, and angular variables, respectively, and an ICC of 0.95 for the OP and 0.92 for the NP volumes.

Means, standard deviations, medians, interquartile ranges, and intergroup differences are given in Table 1. No statistically significant age difference was observed between the groups. Since the skeletal variables (FMA, SNA, SNB, ANB, CoA, and CoGn) were used to form the groups, it was an expected result to have statistically significant differences between the groups. PAS, minAx, and OP volume differed significantly between the groups, whereas no statistically significant difference was observed for OP vertical length and NP volume.
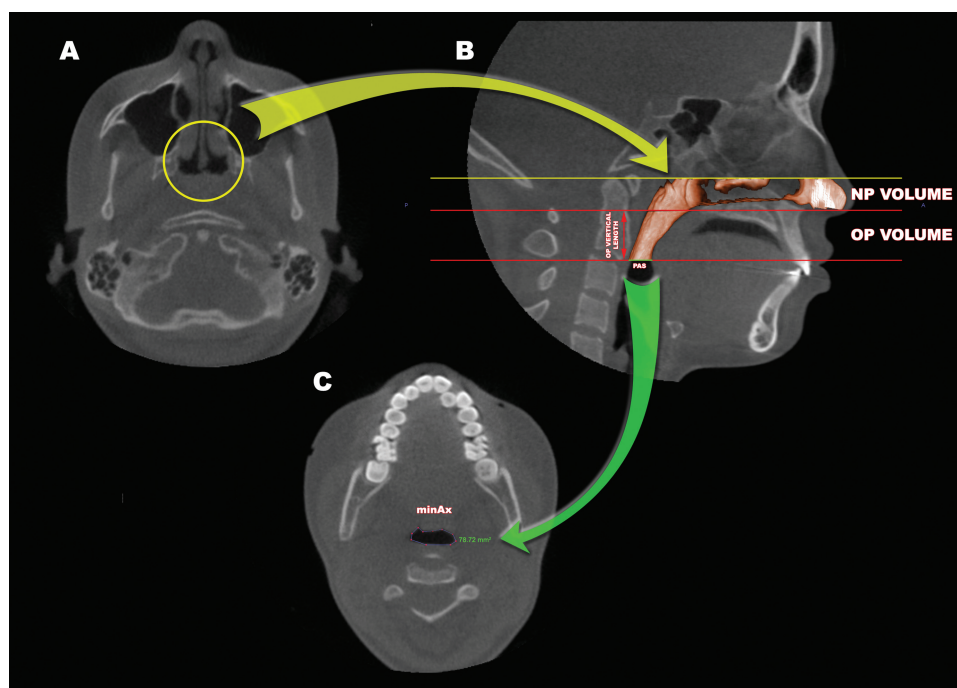
Figure 2 (A) Last axial slice before the nasal septum fuses with the posterior wall of the pharynx (yellow circle) and (B) its representation on the sagittal slice (the uppermost yellow line). Superior and inferior limits of the nasal passage (NP) and oropharyngeal (OP) volume. Sagittal view of the vertical OP length and posterior airway space (PAS) and (C) its reflection and area measurement of oropharynx at PAS level (minAx) on the axial slice.

Table 1 Results of intergroup comparisons using Kruskal–Wallis test. NS, not significant; SD, standard deviation; IQR, interquartile range; CI, Class I; CIIMaxP, Class II maxillary protrusion; CIIMandR, Class II mandibular retrusion; CIIIMaxR, Class III maxillary retrusion; CIIIMandP, Class III mandibular protrusion; PAS, posterior airway space; minAx, area of oropharynx at PAS level on the axial slice; OP, oropharynx; NP, nasal passage.

Skeletal discrepancy		Age at the time of image acquisition (years)	FMA (°)	SNA (°)	SNB (°)	ANB (°)	CoA (mm)	CoGn (mm)	OP vertical length (mm)	PAS (mm)	minAx (mm²)	OP volume (mm³)	NP volume (mm³)
CI (n = 21)	Mean ± SD	15.64 ± 0.50	25.62 ± 2.95	79.92 ± 0.91	77.98 ± 1.06	1.95 ± 0.59	89.81 ± 4.24	110.96 ± 6.43	37.31 ± 4.03	8.58 ± 2.75	172.57 ± 74.94	6956.10 ± 1752.96	6779.14 ± 3055.53
	Median (IQR)	187.00 (9)	25.30 (5.15)	80.20 (1.50)	78.30 (1.85)	1.90 (0.95)	89.70 (6.30)	108.70 (8.85)	36.82 (7.63)	7.53 (3.55)	155.22 (90.54)	6610.00 (2298.00)	6286.00 (3834.00)
	Minimum	179.00	21.00	77.90	76.00	1.00	82.40	103.40	30.40	3.50	76.39	4326.00	2446.00
	Maximum	200.00	30.70	80.90	79.80	3.00	99.00	126.60	43.55	13.91	321.29	11146.00	15040.00
CIIMaxP (n = 21)	Mean ± SD	186.52 ± 7.80	22.58 ± 4.03	84.33 ± 1.76	78.60 ± 1.24	5.73 ± 1.25	92.84 ± 4.96	105.82 ± 5.35	35.79 ± 5.66	8.86 ± 2.24	181.32 ± 72.72	6638.10 ± 3126.54	5209.62 ± 2401.73
	Median (IQR)	185.00 (14)	21.10 (5.30)	84.20 (3.05)	78.90 (1.65)	5.60 (2.05)	92.30 (20.40)	104.80 (7.60)	35.46 (8.00)	8.96 (3.12)	167.60 (96.23)	5821.00 (4379.50)	4193.00 (3373.50)
	Minimum	174.00	19.40	81.20	76.10	3.80	83.10	97.60	23.89	5.33	86.89	3205.00	1905.00
	Maximum	199.00	30.50	87.10	80.00	8.40	103.50	118.60	46.40	13.28	351.10	15546.00	10443.00
CIIMandR (n = 20)	Mean ± SD	184.60 ± 5.34	23.53 ± 4.20	79.57 ± 1.32	74.52 ± 1.16	5.06 ± 1.18	87.92 ± 3.85	104.86 ± 7.19	38.85 ± 4.64	8.39 ± 2.35	160.73 ± 62.29	5837.80 ± 2812.30	4962.80 ± 2130.31
	Median (IQR)	185.00 (7)	21.80 (5.75)	80.00 (2.40)	74.95 (1.68)	5.05 (1.62)	88.35 (5.73)	105.40 (10.75)	40.52 (6.83)	8.49 (3.55)	146.27 (102.29)	5477.50 (3031.50)	4762.50 (3856.25)
	Minimum	176.00	19.50	77.10	71.90	3.20	81.20	93.30	26.23	3.68	66.33	2086.00	2197.00
	Maximum	196.00	29.40	81.00	75.90	7.40	93.40	120.20	44.10	13.25	299.27	14262.00	9042.00
CIIIMaxR (n = 19)	Mean ± SD	187.26 ± 9.69	25.27 ± 4.64	76.14 ± 0.57	77.95 ± 1.30	−1.82 ± 1.29	86.15 ± 3.85	114.34 ± 8.10	36.94 ± 5.06	8.79 ± 2.39	178.51 ± 59.51	6978.32 ± 1804.46	5585.58 ± 1918.99
	Median (IQR)	186 (20)	25.60 (9.80)	76.30 (0.80)	77.60 (2.40)	−2.20 (2.10)	85.70 (4.70)	114.20 (13.70)	37.47 (7.16)	8.47 (3.11)	174.05 (62.96)	6111.00 (2681.00)	5309.00 (2182.00)
	Minimum	175.00	19.30	75.00	76.20	−4.40	80.70	100.10	27.05	3.77	68.82	4667.00	2174.00
	Maximum	204.00	30.00	76.90	80.00	−0.10	95.10	132.30	46.30	12.93	317.61	11471.00	10537.00
CIIIMandP (n = 20)	Mean ± SD	183.55 ± 7.72	22.85 ± 3.52	80.25 ± 0.68	81.39 ± 1.17	−1.15 ± 1.11	93.97 ± 6.76	123.19 ± 7.16	39.63 ± 4.08	10.70 ± 2.22	228.21 ± 69.32	9332.60 ± 2468.67	5541.95 ± 1999.47
	Median (IQR)	182.50 (13)	22.55 (5.20)	80.30 (0.80)	81.35 (1.77)	−1.00 (1.80)	93.45 (8.47)	121.75 (10.23)	40.40 (5.76)	10.39 (3.48)	248.46 (93.81)	8984.00 (4629.00)	5088.00 (2367.50)
	Minimum	170.00	19.00	78.60	80.10	−3.30	81.70	113.50	31.32	6.65	110.82	5727.00	2414.00
	Maximum	198.00	30.50	81.00	83.60	0.40	108.20	141.60	46.95	14.75	387.11	13691.00	10244.00
P		NS	0.03*	0.00***	0.00***	0.00***	0.00***	0.00***	NS	0.03*	0.02*	0.00***	NS

$* P < 0.05$, $** P < 0.01$, $*** P < 0.001$.

Further pairwise comparisons are given in Table 2. PAS (10.70 ± 2.22 mm) and minAx (228.21 ± 69.32 mm) variables were significantly higher for the CIIIMandP group when compared to other groups. CIIIMandP group also presented with the largest OP volume (9332.60 ± 2468.67 mm^3) and a significant difference was observed when compared to other groups. However, there were also significant differences between CI–CIIMandR and CIIMandR–CIIIMaxR groups. CIIMandR subjects had the lowest OP airway volume (5837.80 ± 2812.30 mm^3; Figure 3).

Gender-specific descriptive demographics of the airway variables are given on Table 3. The mean OP and NP volume of the total males were larger compared to females. NP volume of males was statistically significantly higher compared to females. As for the groups, the only statistically significant difference between males and females was observed for CIIIMaxR subjects for the NP volume (males: 6659.25 ± 2296.54 mm^3 and females: 4804.73 ± 1159.20 mm^3, $P < 0.05$).

Bivariate correlations are given on Table 4. SNB, CoGn, OP vertical length, PAS, minAx, and NP volume were significantly positively correlated with OP volume. The ANB angle was significantly negatively correlated with both OP volume and minAx. The variables minAx and OP volume behaved correlated in similar ways, but OP volume showed a significant correlation with the vertical length of OP, while minAx showed a positive but non-significant correlation. NP volume was significantly positively correlated with CoGn, minAx, and OP volume. Stronger correlations were found for OP than NP volumes. The strongest correlation was between OP volume and minAx value ($\rho = 0.73$, $P < 0.001$).

Discussion

Several two-dimensional (2D) and 3D studies have evaluated the relationship between the upper airway and different dentofacial patterns in normal breathing patients

(Solow *et al.*, 1984; Ceylan and Oktay, 1995; Abu Allhaija and Al-Khateeb, 2005; Alves *et al.*, 2008; Grauer *et al.*, 2009; Kim *et al.*, 2010). The current study has been designed to compare skeletal discrepancies taking into account the sagittal position of maxilla and mandible with regard to the cranial base, while other studies either only compared major skeletal discrepancy groups (e.g. Class I, Class II, Class III) with gender subgroups or were conducted using 2D cephalograms. Lenza *et al.* (2010) stated that upper airway cannot be accurately expressed by single linear measurements as performed on cephalograms. Furthermore, a sample size of this size has not been used before in any of the previous studies.

It has been emphasized in the literature that the pharyngeal structures continue to grow rapidly until 13 years of age (Jeans *et al.*, 1981) and in between 14 and 18 years a quiescence period for pharyngeal structures has been reported (Taylor *et al.*, 1996). In long-term follow-up studies, it has been well established that between 22 and 42 years of age, the soft palate becomes longer and thicker and pharyngeal region gets narrower (Kollias and Krogstad, 1999). According to these data, the most stable time period to evaluate mature OP and NP region seems to be between 14 and 18 years of age, which has been conducted in the current study.

Patients with vertical growth patterns tend to have narrower upper pharyngeal width regardless of skeletal discrepancy (de Freitas *et al.*, 2006). In order to eliminate differences caused by severe vertical or horizontal growth patterns, normal growing subjects were selected for this study.

Conventional CT imaging allows precise anatomic evaluation of the airway and surrounding soft tissue structures (Schwab, 1998; Lagravere *et al.*, 2008; Yamashina *et al.*, 2008). However, radiation dose of the conventional CTs is a limiting factor for routine use. On the contrary, CBCT imaging provides an adequate image quality with lower radiation doses and a shorter exposure time (Palomo *et al.*, 2008). The scanning procedure is executed while the patient

Table 2 Results of pairwise comparisons using Mann–Whitney *U*-tests with Bonferroni correction. NS, not significant; CI, Class I; CIIMaxP, Class II maxillary protrusion; CIIMandR, Class II mandibular retrusion; CIIIMaxR, Class III maxillary retrusion; CIIIMandP, Class III mandibular protrusion; PAS, posterior airway space; minAx, area of oropharynx at PAS level on the axial slice; OP, oropharyngeal; NP, nasal passage.

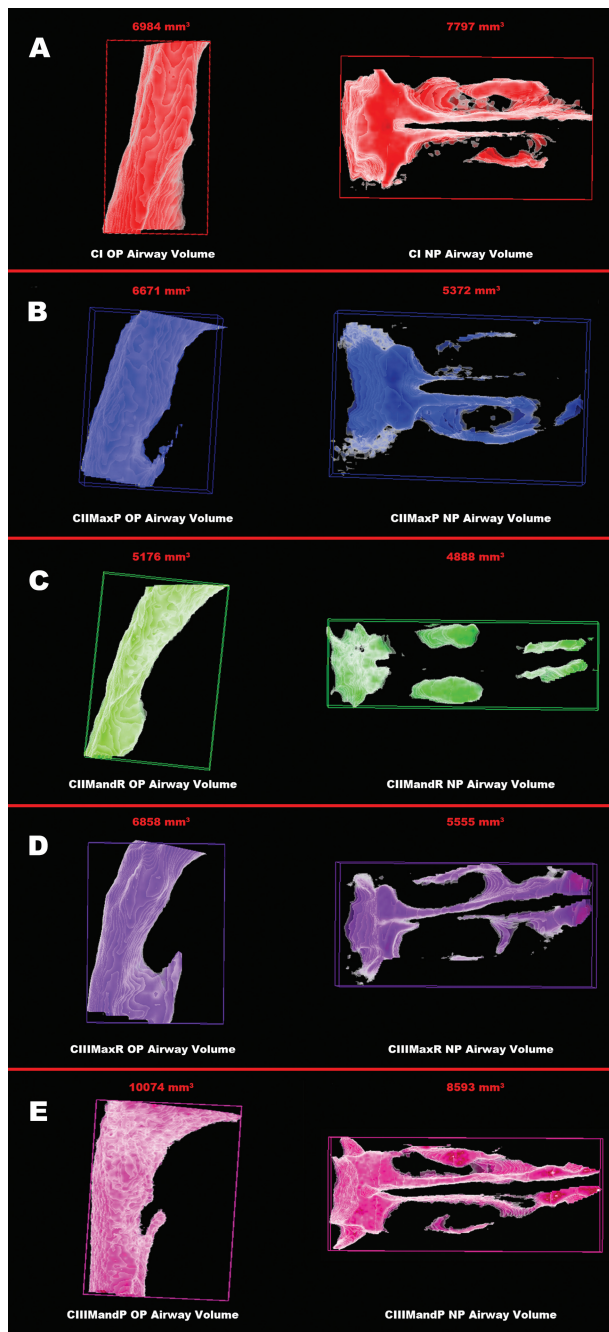|	OP vertical length (mm)	PAS (mm)	minAx (mm^2)	OP volume (mm^3)	NP volume (mm^3)
CI (n = II1)	NS	CIIIMandP*	CIIIMandP*	CIIMandR* CIIIMandP**	CIIMandR*
CIIMaxP (n = II1)	CIIIMandP*	CIIIMandP*	CIIIMandP*	CIIIMandP**	NS
CIIMandR (n = II0)	NS	CIIIMandP**	CIIIMandP**	CI CIIIMaxR* CIIIMandP***	CI*
CIIIMaxR (n = 19)	NS	CIIIMandP*	CIIIMandP*	CIIIMandP**	NS
CIIIMandP (n = II0)	CIIMaxP*	CI* CIIMaxP* CIIMandR* CIIIMaxR*	CI* CIIMaxP* CIIMandR* CIIIMaxR*	CI** CIIMaxP** CIIMandR*** CIIIMaxR**	NS

*$P < 0.05$, **$P < 0.01$, ***$P < 0.001$.

Figure 3 Representation of oropharyngeal (OP) and nasal passage (NP) volumes of an average patient for different groups from the sagittal and axial views, respectively.

InVivo Dental 5.0 was used to "sculpt out" the desired airway volume from the rest of the image. A previous study showed InVivo's highly reliability in its airway volume calculations (El and Palomo, 2010). For that reason we decided to use InVivoDental 5.0 in the present study. It has been mentioned in the literature that malocclusion type does not influence pharyngeal airway width (Watson *et al*., 1968; de Freitas *et al*., 2006; Alves *et al*., 2008). However, Kim *et al*. (2010) and El and Palomo (2011) found that the mean total airway volume of retrognathic patients was significantly smaller than patients with normal antero-posterior relationship. Grauer *et al*. (2009) also confirmed that airway volume and shape differed among patients with different antero-posterior jaw relationships. In a previous study by the same authors (El and Palomo, 2011) the relationship between different Angle classifications and airway volume was evaluated. It was found that Class II subjects had lower OP airway volumes but the answer to which jaw was responsible remained unclear. The current study serves as the next logical step, stratifying which jaw played a larger role. In the current study, it was observed that CIIMandR subjects had the lowest OP and NP airway volume. Especially, the biggest difference was observed between the CIIMandR and CIIIMandP subjects for the OP airway variables (PAS, minAx, and OP volume) where the skeletal sagittal mandibular relationship was in polar opposites. Relatively short and/or posteriorly placed mandible may be forcing the tongue and soft palate back into the pharyngeal space, which may cause a reduction in OP region (Lowe *et al*., 1986). As for the NP volume, although no statistically significant differences were observed between the groups, pairwise comparisons exhibited a significant difference between CI and CIIMandR groups. Kerr (1985) stated that subjects with Class II malocclusion showed smaller nasopharyngeal and adenoid areas. In a 3D study by Kim *et al*. (2010), they found that the nasal airway volume of the Class I subjects was bigger than the Class II subjects, but it was not significant (Kim *et al*., 2010).

The total upper airway volume of males was larger compared to females. Grauer *et al.* (2009) also found that airway volume of males was larger compared to females, especially the upper portion of the airway. The only statistically significant difference observed was for the NP volume in the total sample. When the groups are taken into consideration, it is apparent that the difference is mainly originating from the CIIIMaxR patients where there is also a significant difference between males (6659.25 ± 2296.54 mm^3) and females (4804.73 ± 1159.20 mm^3) for the NP volume. Alves *et al*. (2008) found a significant volume difference between male and female subjects for retropalatal and retroglossal regions for the C3 group but no significant difference was observed for the nasal cavity volume. Although the total number of our subjects was higher than the Alves's study in the total Class III group, the disagreement between studies could be based on relatively

is in an upright position in most of the CBCT machines. Since it has been documented that the upper airway size and shape are prone to change depending upon the body position (Yildirim *et al*., 1991; Pevernagie and Shepard, 1994), Ingman *et al*. (2004) found no significant changes either in nasopharyngeal or in hypopharyngeal soft tissues between the upright and supine positions. However, they noted a significant narrowing of the OP region in supine position. This was not considered as a study bias since all the images were taken under same conditions and position.

Table 3   Descriptive demographics and comparison of male and female subjects within the groups and the total sample. OP, oropharyngeal; PSA, posterior airway space; minAx, area of oropharynx at PAS level on the axial slice; NP, nasal passage.

Skeletal discrepancy	Gender		OP vertical length (mm)	PAS (mm)	minAx (mm^2)	OP volume (mm^3)	NP volume (mm^3)
CI	Male (n = 14)	Mean ± SD	37.61 ± 3.34	8.61 ± 2.81	177.50 ± 72.48	6830.93 ± 1735.83	7050.79 ± 3271.92
	Female (n = 7)		36.71 ± 5.43	8.53 ± 2.87	162.70 ± 84.64	7206.43 ± 1898.64	6235.86 ± 2722.00
P (male/female)			0.70	0.92	0.60	0.55	0.97
CIIMaxP	Male (n = 11)	Mean ± SD	33.65 ± 5.79	9.36 ± 1.88	186.64 ± 67.93	6589.82 ± 2621.10	6164.00 ± 2801.05
	Female (n = 10)		38.15 ± 4.71	8.31 ± 2.57	175.46 ± 80.94	6691.20 ± 3752.77	4159.80 ± 1327.76
P (male/female)			0.16	0.31	0.47	0.43	0.14
CIIMandR	Male (n = 12)	Mean ± SD	39.57 ± 3.65	8.57 ± 2.80	167.55 ± 71.22	6278.92 ± 3248.02	5197.92 ± 2399.94
	Female (n = 8)		37.76 ± 5.94	8.12 ± 1.58	150.50 ± 48.57	5176.13 ± 2013.82	4610.13 ± 1740.73
P (male/female)			0.62	0.38	0.79	0.97	0.57
CIIIMaxR	Male (n = 8)	Mean ± SD	38.64 ± 2.01	9.13 ± 3.44	189.20 ± 79.15	6565.75 ± 1223.65	6659.25 ± 2296.54
	Female (n = 11)		35.71 ± 6.26	8.54 ± 1.36	170.73 ± 42.80	7278.36 ± 2139.54	4804.73 ± 1159.20
P (male/female)			0.43	0.57	0.38	0.91	0.02*
CIIIMandP	Male (n = 12)	Mean ± SD	38.94 ± 4.39	10.66 ± 2.16	229.63 ± 62.34	9630.92 ± 2391.18	6042.00 ± 2244.93
	Female (n = 8)		40.66 ± 3.58	10.77 ± 2.45	226.08 ± 83.23	8885.13 ± 2678.69	4791.87 ± 1363.88
P (male/female)			0.34	0.93	0.87	0.46	0.12
Total	Male (n = 57)	Mean ± SD	37.68 ± 4.46	9.25 ± 2.65	189.79 ± 71.22	7220.44 ± 2630.81	6222.25 ± 2664.24
	Female (n = 44)		37.70 ± 5.34	8.81 ± 2.29	176.91 ± 70.22	7043.39 ± 2769.58	4848.11 ± 1716.60
P (male/female)			0.88	0.26	0.30	0.74	0.07

Table 4   Spearman's correlation coefficients for the OP and NP volume when compared to the variables used for this study. ρ , Spearman's rho; PAS, posterior airway space; minAX, area of oropharynx at PAS level on the axial slice; OP, oropharyngeal; NP, nasal passage.

ρ		FMA	SNA (°)	SNB (°)	ANB (°)	CoA (mm)	CoGn (mm)	OP vertical length (mm)	PAS (mm)	minAx (mm^2)	OP volume (mm^3)	NP volume (mm^3)
minAx (mm^2)	Correlation coefficient	−0.02	−0.10	0.22*	−0.25*	0.02	0.39**	0.18	0.77**		0.73**	0.25*
	P	0.83	0.31	0.03	0.01	0.88	0.00	0.08	0.00		0.00	0.01
OP volume (mm3)	Correlation coefficient	0.00	−0.10	0.35**	−0.38**	0.03	0.43**	0.28**	0.57**	0.73**		0.29**
	P	0.99	0.31	0.00	**0.00**	0.75	0.00	0.01	0.00	0.00		0.00
NP volume (mm3)	Correlation coefficient	−0.14	−0.12	0.14	−0.19	−0.04	0.22*	−0.18	0.09	0.25*	0.29**	
	P	0.17	0.25	0.17	0.06	0.72	0.03	0.08	0.40	**0.01**	**0.00**	

* $P < 0.05$, ** $P < 0.01$, *** $P < 0.001$.

smaller number of male and female subjects in the CIIIMaxR group. The pharyngeal dimensions were not affected by gender in any other group. This finding is in conclusion with various studies (Handelman and Osborne, 1976; Linder-Aronson and Woodside, 1977; Solow *et al.*, 1984; Ceylan and Oktay, 1995).

Joseph *et al.* (1998) noted that hyperdivergent patients had a narrower antero-posterior pharyngeal dimension especially in the nasopharynx at the level of hard palate and in the oropharynx at the level of the tip of the soft palate and mandible. Grauer *et al.* (2009) observed that patients with long faces tended to have an extremely narrow airway, both antero-posteriorly and coronally, when compared to patients with normal faces . In order to eliminate this bias from our study, we excluded severe hypodivergent and hyperdivergent subjects. We did not find any significant correlation between OP or NP volume and mandibular plane angle. The fact that

there is no correlation may be due to eliminating the severe growth patterns (19 < FMA < 31) from our study.

It has been reported that OP area decreases with the increase of the ANB angle (Ceylan and Oktay, 1995). In the current study, we observed that OP volume was significantly negatively correlated with the ANB angle, which is in conjunction with Ceylan and Oktay's findings. There was a positive correlation between SNB angle and OP volume but the correlation between effective mandibular length and OP volume was higher. This finding may suggest that the length of the mandible contributes more to the size and volume of the OP than its position with respect to the cranial base. This agrees with Trenouth and Timms (1999) who measured the length of mandible between gonion and menthon and found that OP airway was positively correlated with length of the mandible. The highest correlation found was between the OP volume and minAx, which accounted for 73 per cent.

Tso *et al.* (2009) also mentioned that there was a high correlation between the most constricted cross-sectional area of the airway and the total airway volume. When the results of this study are taken into account, detection of the sites of restriction of the upper airway is of particular clinical importance in understanding the size and volume of the pharyngeal airway as well as the planning of therapy. Abramson stated that the only cephalometric measurement that exhibited any correlation with the CT parameters was PAS (Abramson *et al.*, 2010). Although PAS was also significantly correlated with the OP volume in our study, the correlation was lower compared to that obtained with minAx. The positive correlation in between the OP volume and NP volume may be the result of using healthy subjects without any airway pathology because situations like nasal congestion, craniofacial anomalies, hypertrophic adenoids, and nasopharyngeal diminished airway space are known to cause a structural narrowing of the pharynx (Fairburn *et al.*, 2007). Kim *et al.* (2010) also found a significant positive correlation between the nasal airway and superior pharyngeal airway.

Some authors consider the most constricted cross-sectional area of the airway region (minAx) more important than the airway volume. The most common argument is that volume measurement does not provide a shape description, and the identification of a section where air passage would be restricted, would be more relevant. The presence of such narrow area would pose a bigger problem, even if everywhere else, the passage is adequate. Tso *et al.* (2009) found that the most constricted cross-sectional area of non-symptomatic patients with normal Class I occlusion varied from 90 to 360 mm^2, which is very close to our findings (minAx value range: 66–387 mm^2). Although they have not performed a correlation between the most constricted cross-sectional area and total volume, the same correlation exists when a Spearman's correlation is executed using their provided data ($\rho = 0.73$, $P = 0.02$). Similarly to the OP volume, minAx is also affected by the sagittal position and length of the mandible, the latter being more impactful. It expected to find a high correlation between the PAS value and minAx since minAx is the axial representation of PAS. However, PAS may not necessarily be the most constricted region of the OP airway because as can be seen on Figure 2, the transverse width of PAS is greater than its antero-posterior dimension, which is always true. This is also another important advantage of 3D studies since 2D studies may easily fail to determine the 'true' restriction site.

Significant correlations were also observed for the NP airway volume. A weak but significant positive correlation was also found between NP volume and effective mandibular length. This can probably be explained by the position of the tongue. When the length of the mandible increases, the tongue appears to lie lower in the floor of the mouth (Graber, 1963). Vig and Cohen (1974) also stated that the decrease in the size of the tongue within the oral cavity is partly due to differential rates of maturation of the skeletodental and muscular elements. This could result in a contributing factor for a larger NP and OP volume. The significant positive correlation that exists between NP airway volume and minAx can be explained by the relationship of OP volume and minAx. As mentioned before, the patients presenting with a larger minAx distance tend to have a larger OP airway volume. Since there is a positive correlation between OP and NP volume, it is acceptable to think that people with larger minAx distance may also have a larger NP volume.

Latest advances in CBCT technology have created a growing demand for 3D imaging of the craniofacial complex. It is apparent that volumetric studies have provided a new perspective on airway studies as well. As can be seen from the outcomes of the current study, it is insufficient to evaluate patients having mandibular retrusion only from a skeletal point of view. For this reason, a detailed analysis of volume and shape of the airway may prove to be a valuable diagnostic addition in orthodontics.

Conclusions

The OP airway volume differed significantly especially between CIIIMandP and CIIMandR groups, with the former showing a larger volume. The only significant difference for the NP volume was between CI and CIIMandR groups where a smaller volume for the CIIMandR group was observed. The minAx was the variable that presented the best correlation with the OP airway volume.

Funding

References

Abramson Z R, Susarla S, Tagoni J R, Kaban L 2010 Three-dimensional computed tomographic analysis of airway anatomy. Journal of Oral and Maxillofacial Surgery 68: 363–371

Abu Allhaija E S, Al-Khateeb S N 2005 Uvulo-glosso-pharyngeal dimensions in different anteroposterior skeletal patterns. Angle Orthodontist 75: 1012–1018

Alves P V, Zhao L, O'Gara M, Patel P K, Bolognese A M 2008 Three-dimensional cephalometric study of upper airway space in skeletal class II and III healthy patients. Journal of Craniofacial Surgery 19: 1497–1507

Angle E H 1907 Treatment of malocclusion of the teeth, 7 edn. S S White Dental Manufacturing Co, Philadelphia

Athanasiou A E, Papadopoulos M A, Mazaheri M, Lagoudakis M 1994 Cephalometric evaluation of pharynx, soft palate, adenoid tissue, tongue, and hyoid bone following the use of a mandibular repositioning appliance in obstructive sleep apnea patients. International Journal of Adult Orthodontics and Orthognathic Surgery 9: 273–283

Ceylan I, Oktay H 1995 A study on the pharyngeal size in different skeletal patterns. American Journal of Orthodontics and Dentofacial Orthopedics 108: 69–75

Dahlberg G 1949 Standard error and medicine. Acta Genetica Statistica Medica 1: 313–321

de Freitas M R, Alcazar N M, Janson G, de Freitas K M, Henriques J F 2006 Upper and lower pharyngeal airways in subjects with Class I and Class II malocclusions and different growth patterns. American Journal of Orthodontics and Dentofacial Orthopedics 130: 742–745

El H, Palomo J M 2010 Measuring the airway in 3 dimensions: a reliability and accuracy study. Am J Orthod Dentofacial Orthop 137:S50 e51–59; discussion S50–52.

El H, Palomo J M 2011 Airway volume for different dentofacial skeletal patterns. Am J Orthod Dentofacial Orthop 139:e511–521.

Fairburn S C et al. 2007 Three-dimensional changes in upper airways of patients with obstructive sleep apnea following maxillomandibular advancement. Journal of Oral and Maxillofacial Surgery 65: 6–12

Graber T M 1963 The "three M's": muscles, malformation and malocclusion. American Journal of Orthodontics 49: 418–450

Grauer D, Cevidanes L S, Styner M A, Ackerman J L, Proffit W R 2009 Pharyngeal airway volume and shape from cone-beam computed tomography: relationship to facial morphology. American Journal of Orthodontics and Dentofacial Orthopedics 136: 805–814

Gwynne-Evans E 1958 Discussion on the mouth-breather. Proceedings of the Royal Society of Medicine 51: 279–282

Handelman C S, Osborne G 1976 Growth of the nasopharynx and adenoid development from one to eighteen years. Angle Orthodontist 46: 243–259

Ingman T, Nieminen T, Hurmerinta K 2004 Cephalometric comparison of pharyngeal changes in subjects with upper airway resistance syndrome or obstructive sleep apnoea in upright and supine positions. European Journal of Orthodontics 26: 321–326

Jeans W D, Fernando D C, Maw A R, Leighton B C 1981 A longitudinal study of the growth of the nasopharynx and its contents in normal children. British Journal of Radiology 54: 117–121

Johnston C D, Richardson A 1999 Cephalometric changes in adult pharyngeal morphology. European Journal of Orthodontics 21: 357–362

Joseph A A, Elbaum J, Cisneros G J, Eisig S B 1998 A cephalometric comparative study of the soft tissue airway dimensions in persons with hyperdivergent and normodivergent facial patterns. Journal of Oral and Maxillofacial Surgery 56: 135–139, discussion 139–140

Kerr W J 1985 The nasopharynx, face height, and overbite. Angle Orthodontist 55: 31–36

Kim Y J, Hong J S, Hwang Y I, Park Y H 2010 Three-dimensional analysis of pharyngeal airway in preadolescent children with different anteroposterior skeletal patterns. American Journal of Orthodontics and Dentofacial Orthopedics 137: 306 e301–e311, discussion 306–307

Kirjavainen M, Kirjavainen T 2007 Upper airway dimensions in Class II malocclusion. Effects of headgear treatment. Angle Orthodontist 77: 1046–1053

Kluemper G T, Vig P S, Vig K W 1995 Nasorespiratory characteristics and craniofacial morphology. European Journal of Orthodontics 17: 491–495

Kollias I, Krogstad O 1999 Adult craniocervical and pharyngeal changes—a longitudinal cephalometric study between 22 and 42 years of age. Part II: morphological uvulo-glossopharyngeal changes. European Journal of Orthodontics 21: 345–355

Lagravere M O, Carey J, Toogood R W, Major P W 2008 Three-dimensional accuracy of measurements made with software on cone-beam computed tomography images. American Journal of Orthodontics and Dentofacial Orthopedics 134: 112–116

Leech H L 1958 A clinical analysis of orofacial morphology and behavior of 500 patients attending an upper respiratory research clinic. Dental Practice 9: 57–68

Lenza M G, Lenza M M, Dalstra M, Melsen B, Cattaneo P M 2010 An analysis of different approaches to the assessment of upper airway morphology: a CBCT study. Orthodontics and Craniofacial Research 13: 96–105

Linder-Aronson S 1970 Adenoids. Their effect on mode of breathing and nasal airflow and their relationship to characteristics of the facial skeleton and the denition. A biometric, rhino-manometric and cephalometro-radiographic study on children with and without adenoids. Acta Oto-laryngologica Supplementum 265: 1–132

Linder-Aronson S, Woodside D G 1977 The growth in the sagittal depth of the bony nasopharynx in relation to some other facial variables. Transactions of the European Orthodontics Society 1977: 69–83

Lowe A A, Santamaria J D, Fleetham J A, Price C 1986 Facial morphology and obstructive sleep apnea. American Journal of Orthodontics and Dentofacial Orthopedics 90: 484–491

Ludlow J B, Ivanovic M 2008 Comparative dosimetry of dental CBCT devices and 64-slice CT for oral and maxillofacial radiology. Oral Surgery, Oral Medicine, Oral Pthology, Oral Radiology, and Endodontics 106: 106–114

Mah J K, Huang J C, Choo H 2010 Practical applications of cone-beam computed tomography in orthodontics. Journal of the American Dental Association 141(Suppl 3): 7S–13S

Martin O, Muelas L, Vinas M J 2006 Nasopharyngeal cephalometric study of ideal occlusions. American Journal of Orthodontics and Dentofacial Orthopedics 130: 436 e431–e439

Martin O, Muelas L, Vinas M J 2011 Comparative study of nasopharyngeal soft-tissue characteristics in patients with Class III malocclusion. American Journal of Orthodontics and Dentofacial Orthopedics 139: 242–251

McNamara J A Jr 1984 A method of cephalometric evaluation. American Journal of Orthodontics 86: 449–469

Moore A 1972 Observations on mouth breathing. Bulletin New Zealand Society of Periodontology 33: 9–11

Palomo J M, Rao P S, Hans M G 2008 Influence of CBCT exposure conditions on radiation dose. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics 105: 773–782

Pevernagie D A, Shepard J W Jr, 1994 Effects of body position on upper airway size and shape in patients with obstructive sleep apnea. Acta Psychiatrica Belgica 94: 101–103

Ricketts R M 1968 Respiratory obstruction syndrome. American Journal of Orthodontics 54: 495–507

Schwab R J 1998 Upper airway imaging. Clinics in Chest Medicine 19: 33–54

Solow B, Siersbaek-Nielsen S, Greve E 1984 Airway adequacy, head posture, and craniofacial morphology. American Journal of Orthodontics 86: 214–223

Taylor M, Hans M G, Strohl K P, Nelson S, Broadbent B H 1996 Soft tissue growth of the oropharynx. Angle orthodontist 66: 393–400

Tourne L P 1991 Growth of the pharynx and its physiologic implications. American Journal of Orthodontics and Dentofacial Orthopedics 99: 129–139

Trenouth M J, Timms D J 1999 Relationship of the functional oropharynx to craniofacial morphology. Angle orthodontist 69: 419–423

Trotman C A, McNamara J A Jr, Dibbets J M, van der Weele L T 1997 Association of lip posture and the dimensions of the tonsils and sagittal airway with facial morphology. Angle orthodontist 67: 425–432

Tso H H, Lee J S, Huang J C, Maki K, Hatcher D, Miller A J 2009 Evaluation of the human airway using cone-beam computerized tomography. Oral Surgery, Oral Medicine, Oral Pathology, Oral Radiology, and Endodontics 108: 768–776

Vig P S, Cohen A M 1974 The size of the tongue and the intermaxillary space. Angle orthodontist 44: 25–28

Watson R M Jr, Warren D W, Fischer N D 1968 Nasal resistance, skeletal classification, and mouth breathing in orthodontic patients. American Journal of Orthodontics 54: 367–379

Yamashina A, Tanimoto K, Sutthiprapaporn P, Hayakawa Y 2008 The reliability of computed tomography (CT) values and dimensional measurements of the oropharyngeal region using cone beam CT: comparison with multidetector CT. Dento Maxillo Facial Radiology 37: 245–251

Yildirim N, Fitzpatrick M F, Whyte K F, Jalleh R, Wightman A J, Douglas N J 1991 The effect of posture on upper airway dimensions in normal subjects and in patients with the sleep apnea/hypopnea syndrome. American Review of Respiratory Disease 144: 845–847