Research Square

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CBCT-based three-dimensional morphometric analysis of the upper airway and its influencing factors in skeletal Class II average-angle patients across different bone ages

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Abstract

Objective

Previous studies have largely treated skeletal Class II patients as a homogeneous group for overall analysis, without fully accounting for subgroup differences in vertical facial patterns or variations in developmental timing. Consequently, a systematic understanding of the associations between upper airway morphology, hyoid position, and craniofacial morphology remains insufficient, which limits the formulation of precise clinical intervention strategies. This study aims to analyze the three-dimensional morphological changes of the upper airway and their associated influencing factors in skeletal Class II average-angle patients, stratified by cervical vertebral bone age staging, so as to provide evidence for the development of stage-specific orthodontic treatment strategies.

Methods

A total of 205 skeletal Class II average-angle patients were enrolled and divided into four groups (T1–T4) according to cervical vertebral bone age staging. Upper airway morphology, hyoid position, and craniofacialparameters were assessed using cone-beam CT (CBCT) three-dimensional reconstruction combined with Dolphin and WinCeph software. Inter-group comparisons were conducted using analysis of variance (ANOVA). Spearman correlation analysis and multiple linear regression analysis were used to identify independent predictors of upper airway morphology.

Results

In females, total upper airway volume and nasopharyngeal volume increased significantly at stages T2 and T4, whereas palatopharyngeal and laryngopharyngeal volumes showed significant increased only at stage T4 ($P < 0.05$). In males, significant volumetric increments across all airway segments were observed predominantly at stages T3 and T4 ($P < 0.05$). Multiple regression analysis revealed that in females, the positive predictors of total upper airway volume included bone age stages T2 and T4, Mx'-Mx, H-RGn, and H-CVP. In males, the positive predictors comprised bone age stage T3, H-RGn, and H-CVP.

Conclusion

Upper airway volume in skeletal Class II average-angle patients exhibits a sex-dimorphic developmental pattern across bone age stages. Females display a biphasic growth pattern with leap-like increases at T2 and T4, whereas males demonstrate a steady and pronounced growth spurt from T3 to T4. Hyoid position parameters (H-RGn and H-CVP) consistently emerge as key determinants of upper airway volume, while the contribution of jaw morphology—primarily maxillary width—varies by gender.

Background

Skeletal Class II malocclusion, characterized by maxillary protrusion, mandibular retrognathia, or a combination thereof, markedly impairs facial aesthetics, masticatory function, and overall stomatognathic health [1]. Recent studies have increasingly focused on its impact on upper airway morphology and hyoid position. Accumulating evidence indicates that mandibular retrognathia displaces posterior-inferior hyoid displacement, resulting in a significantly diminished upper airway volume in Class II patients relative to Class I and III patients, particularly at the oropharyngeal level [2–7]. Chen W et al. confirmed a more inferiorly positioned hyoid and tongue in this population [8], and subsequent investigations have further demonstrated that such displacement mechanically constricts the oropharyngeal and glossopharyngeal spaces, thereby elevating the risk of airway collapse [9–11]. Moreover, Anandarajah et al. reported that pharyngeal airway dimensions are significantly correlated with age, skeletal maturity, and three-dimensional craniofacial morphology [12]. Nevertheless, the majority of existing studies have treated Class II patients as a homogeneous entity, overlooking the confounding effects of vertical facial pattern and variations in developmental stage. This oversimplification has resulted in an incomplete understanding of the interplay among airway morphology, hyoid position, and jaw parameters, thereby hindering the development of precise, individualized clinical intervention strategies.Vertical facial pattern constitutes a critical confounder in the assessment of upper airway morphology. Previous studies have confirmed that high-angle patients, owing to clockwise rotation of the mandible and consequent further posterior-inferior displacement of the hyoid, exhibit narrower airway dimensions and an elevated risk of collapse compared with average-angle patients [13, 14]. Consequently, the prevailing body of airway research has either concentrated on high-angle subgroups or adjusts vertical pattern as a covariate, leaving average-angle Class II patients severely understudied. In this particular subgroup, the isolated sagittal discrepancy (mandibular retrognathia) induces hyoid displacement and oropharyngeal narrowing through mechanisms fundamentally distinct from those operative in high-angle patients. More critically, the dynamic developmental trajectory of airway morphology in average-angle patients has yet to be elucidated, which impedes clinicians' ability to determine the optimal timing for functional appliance therapy and deprives them of objective indicators for assessing post-treatment airway improvement potential. Bone age, as determined by cervical vertebral maturation staging, affords a more accurate predictor of mandibular growth peaks and residual growth capacity than chronological age. Using bone age staging as a temporal framework to characterize airway development can effectively circumvent bias arising from interindividual heterogeneity in growth velocity. Nonetheless, research investigating the three-dimensional morphological characteristics of the airway in skeletal Class II average-angle patients based on cervical vertebral maturation(CVM) staging remains conspicuously lacking, with a particular paucity of studies addressing dynamic changes in regional airway volumes and their contributing factors.

To address these gaps, the present study rigorously excluded the dual confounding influences of sagittal and vertical skeletal patterns, focusing specifically on skeletal Class II average-angle patients as a defined target population. Utilizing cone-beam computed tomography (CBCT) three-dimensional measurement techniques, we stratified patients according to CVM bone age stages T1 through T4 and

systematically characterized the dynamic alterations in both total and regional upper airway volume. The effects of hyoid bone position and jaw morphology on airway volume were investigated, and sex-related differences were also examined. The core objectives of this study are twofold: (1) to delineate the bone age-related trajectory of upper airway morphological changes and associated sex differences in this population; and (2) to determine the independent and sex-specific contributions of hyoid position, jaw morphology, and bone age stage to airway volume. Ultimately, this study aims to establish a bone age-based risk assessment framework and to inform individualized, stage-specific treatment strategies, with the overarching goal of achieving an optimal integration of craniofacial functional stability and facial aesthetic harmony.

Material and methods

1. Study Subjects

A total of 205 patients aged 6–25 years with skeletal Class II average-angle skeletal patterns, who attended the Department of Orthodontics at Hebei Medical University Stomatological Hospital between October 2018 and October 2025, were selected for this study, including 103 males and 102 females. Inclusion criteria: (1) newly diagnosed cases with CBCT imaging data; (2) ANB > 4.7°, 22° ≤ FH-MP ≤ 32°; (3) upright-position CBCT scan range: the upper boundary at least including the cranial base, and the lower boundary at least including the superior margin of the fifth cervical vertebra. Exclusion criteria: (1) history of orthodontic treatment or craniofacial surgery; (2) systemic diseases affecting skeletal muscle function; (3) soft tissue lesions such as tonsillar hypertrophy grade II or above, and adenoid hypertrophy grade II; (4) patients with congenital cleft lip and palate; (5) overweight or obese patients (BMI > 28 kg/m²). According to the Baccetti modified cervical vertebral maturation method [15] and the study by Phelan A et al. [16], patients were divided into four stages: T1 (pre-pubertal): n = 36 (22 males, 14 females). T2 (pubertal): n = 61 (34 males, 27 females). T3 (post-pubertal): n = 57 (30 males, 27 females). T4 (young adult): n = 51 (17 males, 34 females).

2. CBCT Acquisition

All patients were scanned in the standing position, with the head and neck naturally relaxed, looking straight ahead, the Frankfort horizontal plane parallel to the floor, the teeth in centric occlusion, and swallowing suspended. A KaVo 3D eXam CBCT unit (USA) was used in this study. Scan parameters: single 360° rotational scan, tube voltage 120 kV, tube current 5 mA, slice thickness 0.3 mm, single scan range: 23 cm × 17 cm, scan time 17.8 s.

3. CBCT Image Processing and Measurement Parameters

The CBCT data of the patients were saved in DICOM format and imported into Dolphin Imaging 11.95 software (Infolab snc, Italy). First, the horizontal plane was corrected on the coronal view to make the line connecting the bilateral infraorbital margins parallel to the horizontal plane, and then the Frankfort horizontal plane was made parallel to the horizontal plane on the sagittal view. A total of 36 upper airway

measurement parameters were obtained (Figure 1, Table 1), as well as measurements of maxillary and mandibular widths (Figure 2-A). The intersection points of the left and right zygomaticoalveolar crests with the maxillary tuberosity contour were designated as JL and JR points, respectively, and the distance between these two points was defined as maxillary width Mx'–Mx. The most lateral points of the left and right mandibular angle processes were designated as AGL and AGR points, respectively, and the distance between these two points was defined as mandibular width Go'–Go. The stored lateral cephalometric radiographs were imported into WinCeph 9.0 software (RISE Corporation, Japan). After marking the required points on the lateral radiograph, the system automatically generated 6 hyoid bone measurement parameters (Figure 2-B), as well as 22 jaw morphology measurement parameters in addition to maxillary and mandibular widths (Figure 2-C). Among these, items 7–8 represent incisor relationships, item 9 represents the cranial base angle, items 10–14 represent sagittal measurements, items 15–23 represent vertical measurements, item 24 and Mx'–Mx represent maxillary morphological parameters, and items 25–28 and Go'–Go represent mandibular morphological parameters.

Statistical analysis

All measurement data were statistically processed using SPSS 21.0 software (IBM Corporation, USA). The Shapiro–Wilk test was used to test data normality, and Levene's test was used to assess homogeneity of variance. For airway measurement parameters, one-way ANOVA was performed for intergroup comparisons among the four bone age stages. If the ANOVA results showed significant differences ($P < 0.05$), Tukey's HSD test was subsequently used to determine specific intergroup differences. When data did not follow a normal distribution or variances were unequal, non-parametric tests (Mann–Whitney U test) were used for data analysis. The associations between total airway volume and continuous variables such as hyoid bone and jaw measurements were evaluated using Spearman correlation analysis. For significantly correlated variables, linear regression analysis was further performed to identify the most relevant influencing factors for upper airway morphology.

Results

1. Growth trend of the upper airway (Table 2–3)

1.1 Overall trend

With the exception of AP2 and AP3 in both sexes and L1 in males, all other upper airway measurement parameters increased significantly with growth and development ($P < 0.01$).

1.2 Changes in airway volume

In females, VT and V1 showed two distinct periods of rapid growth: at T2 ($P < 0.05$) and at T4 ($P < 0.01$). V2 and V4 increased significantly at T4 ($P < 0.05$). V3 showed no statistically significant differences between any adjacent stage groups ($P > 0.05$). In males, VT and all segmental volumes increased significantly at T3 and T4 ($P < 0.05$).

1.3 Changes in mid-sagittal airway area

In females, ST, S1, and S2 increased significantly at T4 ($P < 0.01$). In males, ST, S2, and S3 increased significantly at T3 and T4, while S1 and S4 increased significantly at T4 ($P < 0.01$).

1.4 Changes in airway length

Total upper airway length increased continuously throughout development in both sexes, with statistically significant differences between each adjacent stage group ($P < 0.01$). The changing trends of segmental airway lengths were similar between males and females, with slight differences.

1.5 Changes in cross-sectional parameters

In females, MCA increased significantly at T4 ($P < 0.01$). In males, MCA increased significantly at T3 and T4 ($P < 0.01$).

In females, CSA1, CSA2, and CSA4 increased significantly at T4; LAT1 increased significantly at T3 and T4; LAT2 increased significantly at T4; LAP3 increased significantly at T3; LAP4 increased significantly at T2 and T4; and AP1 increased significantly at T2 and T4 ($P < 0.05$). In males, most cross-sectional area and transverse diameter parameters showed a trend of rapid growth during T3 and T4; AP1 increased significantly at T3 and T4, and AP4 increased significantly at T4 ($P < 0.05$). However, AP2 and AP3 (oropharyngeal transverse diameters) showed no significant changes with growth and development in either sex ($P > 0.05$).

The growth trends of V1, V2, V3, V4, VT, ST, LT, and MCA are shown in Figure 3.

2. Multiple linear regression analysis of total upper airway volume

To identify the independent factors influencing VT, this study used VT as the dependent variable. Skeletal maturation stage, hyoid position indicators (H–FH, H–RGn, H–CVP), and maxillomandibular indicators (Mx'–Mx, Go'–Go, ANS–Me, N–Me, S–PNS, Co–Gn) were included as independent variables. Variables with high collinearity were excluded prior to analysis. In the multiple linear regression analysis for females, the model $R^2 = 0.615$, and skeletal maturation stages T2 and T4 both showed significant positive effects on VT ($P < 0.05$); among maxillomandibular and hyoid variables, Mx'–Mx, H–RGn, and H–CVP were also significantly positively correlated with VT ($P < 0.05$). The results are detailed in Table 4 and Figure 4-A. In the multiple linear regression analysis for males, the model $R^2 = 0.675$, and skeletal maturation stage T3 showed a significant positive effect on VT ($P < 0.01$); among maxillomandibular and hyoid variables, H–RGn and H–CVP were significantly positively correlated with VT ($P < 0.01$). The results are detailed in Table 5 and Figure 4-B. The estimated values for T1 and T3 were referenced to T2, and the estimated value for T4 was referenced to T3 (all derived from the same model).

Disscussion

1. Growth trend of the upper airway in skeletal Class II patients with average vertical facial type

Craniomaxillofacial growth and development involves morphological and dimensional changes in length, width, and height that occur in conjunction with skeletal maturation. This process is not linear or indefinitely sustained; rather, it exhibits non-uniform, stage-specific developmental characteristics across different periods and directions. Previous studies have found sex differences in the development of the upper airway and jaws [17–20]. Therefore, the present study stratified patients by sex and strictly controlled for sagittal and vertical skeletal facial types to effectively minimize the influence of confounding variables and enhance the specificity of the results.

This study revealed that the development of the upper airway in skeletal Class II patients with average vertical facial type exhibited significant sex differences and skeletal maturation dependency. In females, total upper airway volume and nasopharyngeal volume showed two significant growth spurts—at T2 (adolescence) and T4 (young adulthood)—exhibiting an intermittent biphasic growth pattern, while palatopharyngeal volume, hypopharyngeal volume, and most sagittal area parameters increased rapidly primarily at T4 (young adulthood). These findings indicate that upper airway development in females is not only synchronized with the pubertal growth spurt but also includes a significant growth phase during the later stages of development. Notably, glossopharyngeal volume in females did not change significantly with skeletal maturation. In contrast to the findings of Li et al. [21], who reported an age-related increase in glossopharyngeal volume in females, we suggest that this discrepancy may be attributed to differences in skeletal facial type control. By strictly restricting the sample to patients with average vertical facial type, this study excluded the compensatory dilatory effects of vertical development on the glossopharyngeal region, thereby revealing the inherently restricted developmental characteristics of this region in skeletal Class II patients. This finding carries important clinical implications: in female skeletal Class II patients, the glossopharyngeal region may represent a "bottleneck area" of upper airway development that is unlikely to achieve significant improvement through natural growth even by young adulthood (T4). Early mechanical intervention (e.g., functional appliance-induced mandibular advancement) may be more necessary.

Male patients exhibited a distinctly different developmental pattern, characterized by a highly concentrated and continuous growth of the upper airway during late adolescence (T3) and young adulthood (T4). All volume and cross-sectional area parameters increased significantly during these two stages, which is consistent with the male growth and developmental characteristics of later pubertal onset, longer duration, and greater overall growth magnitude. Notably, T3 had a significant positive effect on changes in total upper airway volume in males.

Chuang et al. [22] found that as airway length increases, its morphology changes accordingly, with transverse diameter growth being more pronounced than anteroposterior diameter growth, resulting in a progressively elliptical cross-section. The present study is consistent with these findings. Numerically, sagittal diameters in males were similar to those in females, while all other parameters were larger in males, suggesting that morphological changes of the upper airway during development are more

pronounced in males, with the cross-section tending toward an oblate elliptical shape. From a biomechanical perspective, an oblate elliptical airway is more prone to anterior–posterior wall collapse under negative pressure and represents a high-risk morphology for airway collapse. This feature may partially explain the epidemiological phenomenon of significantly higher OSA prevalence in males than in females, suggesting that orthodontic treatment strategies should more actively incorporate airway function protection alongside facial profile optimization.

2. Correlation of upper airway with hyoid position and maxillomandibular indicators in skeletal Class II patients with average vertical facial type

2.1 Anatomical association between hyoid position and the upper airway

Hyoid position is complexly associated with airway space and serves as an important reference indicator for assessing upper airway morphology [23–26]. Jiang et al. measured airway parameters and hyoid position in 254 patients and found that most hyoid position parameters were significantly correlated with upper airway volume [27], which is consistent with the findings of the present study. Through multiple linear regression analysis, this study further confirmed that, after adjusting for maxillomandibular morphology and skeletal maturation, H–RGn and H–CVP remained significantly positively correlated with total upper airway volume. A greater distance from the hyoid to the retrognathion was associated with a larger total upper airway volume. Previous studies on patients with obstructive sleep apnea (OSA) have shown that a smaller hyoid–retrognathion distance is significantly correlated with mandibular retrusion, i.e., a relatively posterior chin position [28]. This indicator is commonly used in craniomaxillofacial measurements to assess the risk of mandibular retrusion and airway morphology [29]. H–CVP reflects the distance from the hyoid to the prevertebral plane, with larger values corresponding to greater total upper airway volume. A systematic review and meta-analysis on predictors of treatment efficacy for obstructive sleep apnea with mandibular advancement devices reported that the distance from the hyoid to the third cervical vertebra is one of the important anatomical predictors of treatment outcome, with shorter distances associated with higher treatment success rates [30], further indicating a close relationship between this indicator and upper airway morphology. De Bataille et al. [31] found that anterior hyoid displacement can pull the tongue forward via muscles such as the genioglossus, thereby reducing tongue base compression against the posterior pharyngeal wall. Animal experiments have further confirmed [32] that both isolated mandibular advancement and isolated hyoid repositioning can reduce pharyngeal critical closing pressure and alleviate upper airway collapsibility; when combined, the effects are additive, further suggesting that hyoid position is a key factor influencing upper airway morphology.

2.2 Impact of maxillomandibular morphology on the upper airway

Maxillomandibular position and morphological characteristics are closely related to upper airway morphology. Studies have shown that increases in maxillary and mandibular length can effectively enlarge oropharyngeal airway volume [33], which is similar to the results of the present study. Unlike previous studies, the present study found that maxillary width was significantly positively correlated with

upper airway volume, and this correlation remained statistically significant in females after adjusting for other variables in the multiple linear regression model. In contrast, mandibular length and facial height parameters were positively correlated with total upper airway volume but did not reach statistical significance after correction for other variables. These findings suggest that transverse maxillary development contributes more directly to upper airway expansion than sagittal and vertical mandibular development. The palatine process of the maxilla is located at the floor of the nasal cavity, the roof of the oral cavity, and the anterior wall of the pharynx, and its transverse width directly determines the width of the nasal floor and the transverse diameter of the pharyngeal cavity. An increase in maxillary width can enlarge the nasopharyngeal and palatopharyngeal transverse diameters, providing a more spacious attachment space for the soft palate and lateral pharyngeal walls. Conversely, transverse maxillary deficiency is often accompanied by a high-arched palate and a narrow nasal floor, leading to reduced nasal ventilation [34] and forcing patients into mouth breathing. Long-term mouth breathing can induce clockwise rotation of the mandible and posterior–inferior displacement of the tongue position, thereby reducing the sagittal diameter of the glossopharyngeal and hypopharyngeal spaces and diminishing upper airway patency.

In conclusion, the morphology of the upper airway is closely related to the position of the hyoid bone and the morphological characteristics of the jaws. Clinicians should develop individualized treatment plans based on the patient's growth and developmental stage, aiming to improve facial aesthetics while also optimizing airway function. We should avoid overlooking the potential risks associated with changes in airway morphology merely for the sake of dental alignment, and truly achieve the integration of function and aesthetics.

3. Limitations and future directions

Currently, imaging examinations for young children are mainly based on lateral cephalometric radiographs and panoramic radiographs, which involve relatively low radiation doses. Most young children who undergo CBCT examinations are admitted for treatment due to impacted teeth, which results in a relatively limited sample size for the T1 stage. In addition, as a cross-sectional study, although it reveals the overall trend of upper airway growth and development, it cannot track the longitudinal trajectory of changes in individuals over time. Future studies may incorporate fluid dynamics simulations to further explore the intrinsic relationship between upper airway morphological development and functional development, thereby providing a more precise theoretical basis for early clinical intervention.

Conclusions

1. In skeletal Class II average-angle patients, upper airway volume tends to increase with skeletal maturation. Females exhibit an intermittent biphasic growth pattern, with notable increments occurring during puberty (T2) and again in young adulthood (T4) . In contrast, males demonstrate a

continuous growth trajectory from late puberty (T3) and through young adulthood (T4), with the most pronounced increase observed at the T3 stage.

2.Total upper airway volume shows a significant positive correlation with hyoid bone positional parameters, among which H-RGn and H-CVP emerge as key influencing factors.

3.A positive correlation is also found between total upper airway volume and craniofacial dimensions. Notably, the influence of maxillary width on airway volume is more pronounced in females than in males, underscoring the importance of considering gender-specific differences in combined orthodontic and airway-focused diagnosis and treatment planning.

Declarations

Ethics approval and consent to participate

This study was conducted in accordance with the Declaration of Helsinki and was approved by the Ethics Committee of [Hebei Medical University Stomatological Hospital] (Approval No. [2026011]). Informed consent was obtained from all individual participants included in the study. For participants under 18 years of age, informed consent was obtained from their legal guardians.

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Data availability

The data underlying this article cannot be shared publicly due to the privacy of individuals that participated in the study. The data will be shared on reasonable request to the corresponding author.

Author contribution

Y.L. and Z.M. have drafted the work or substantively revised it. W.L. interpreted data. L.H. and Y. Z. collected data. X. L. contributed to the background investigation and visualization of the study. Y. Y. performed the statistical analysis. C. L. designed the work.All authors reviewed the manuscript.

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Tables

Tables 1 to 5 are available in the Supplementary Files section.

Figures

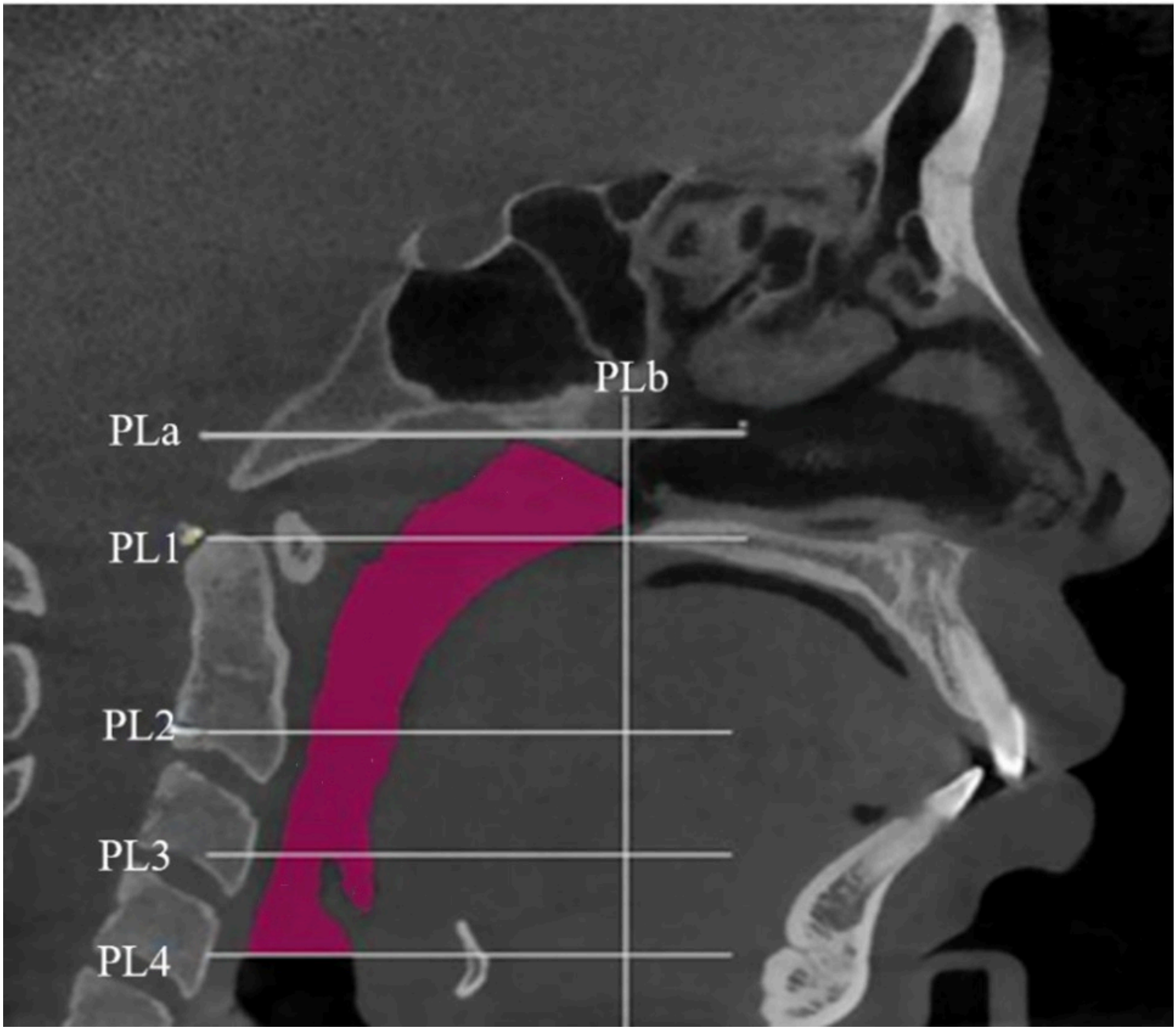


Figure 1

The partitions of upper airway.

PLa, PL1, PL2, PL3, and PL4 are all horizontally parallel planes, while PLb is a vertical plane. From top to bottom, the order is: PLa (upper boundary) → PL1 (nasopharynx/palatopharyngeal junction) → PL2 (palatopharyngeal/glossopharyngeal junction) → PL3 (glossopharyngeal/hypopharyngeal junction) → PL4 (lower boundary)

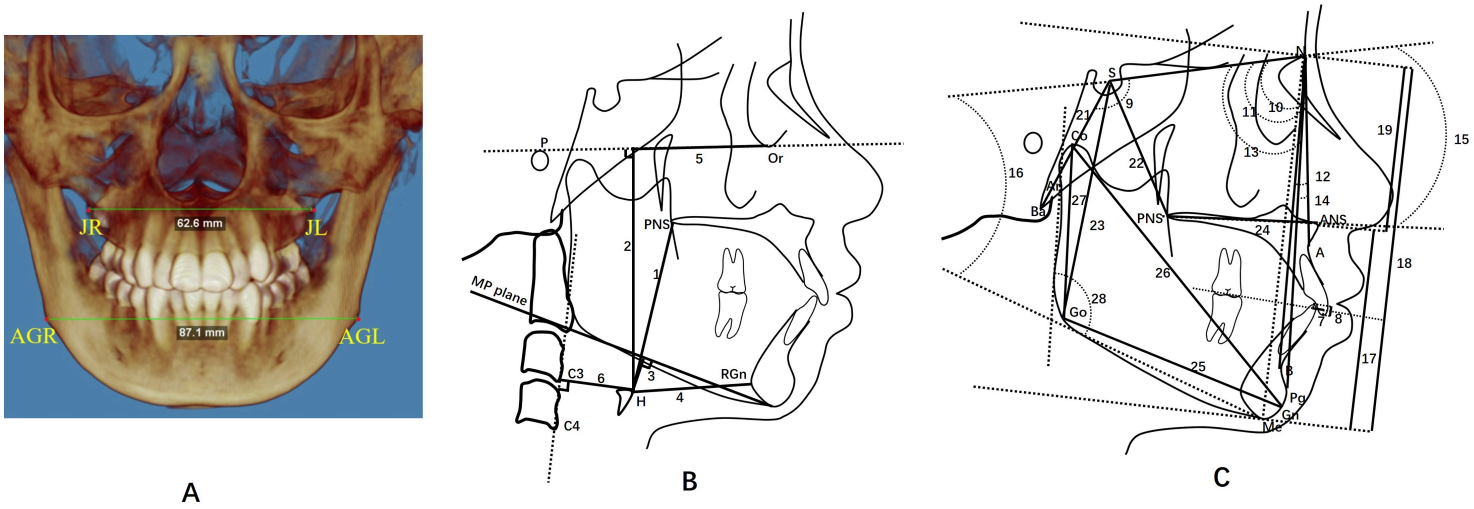


Figure 2

Morphometric parameters of the hyoid, maxilla, and mandible.

1.H-PNS; 2.H-FH; 3.H-MP; 4.H-RGn; 5.H-Or; 6.H-CVP; 7.Overjet; 8. Overbite; 9.SNBa; 10.SNA; 11. SNB; 12.ANB; 13.SNPg; 14.ANPg; 15.SN-NL; 16.SN-MP; 17.ANS-Me; 18.N-Me; 19.N-ANS; 20.LAFH=17/18; 21.S-Ba; 22.S-PNS; 23.S-Go; 24.ANS-PNS; 25.Go-Gn; 26.Co-Gn;27.Co-Go; 28.Gonial angle

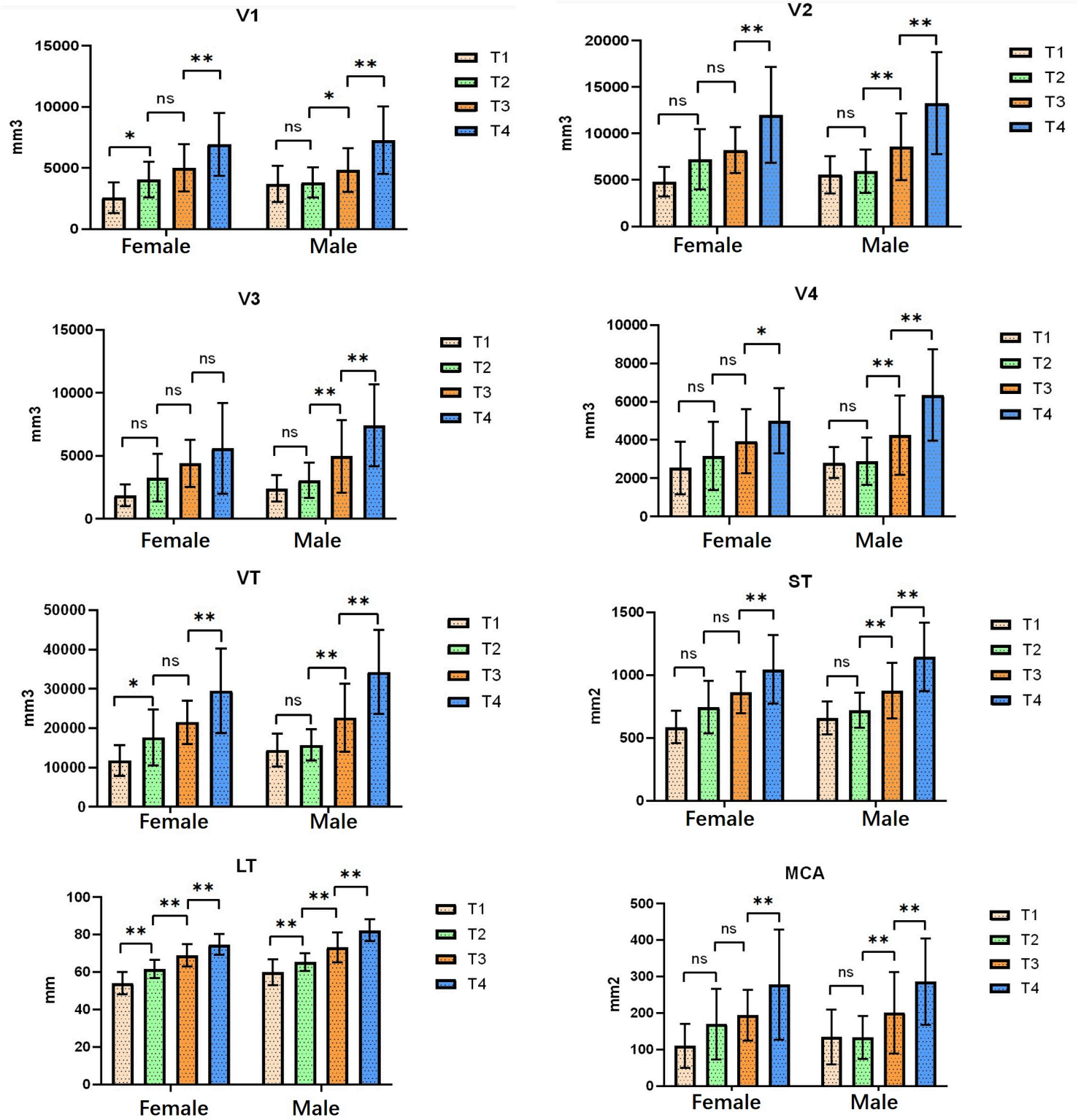


Figure 3

The growth of the upper airway .

Bars represent group means, and error bars indicate ±1 standard deviation (SD). “ns” indicates no statistically significant difference,“*” indicates $P < 0.05$, and “**” indicates $P < 0.01$.)

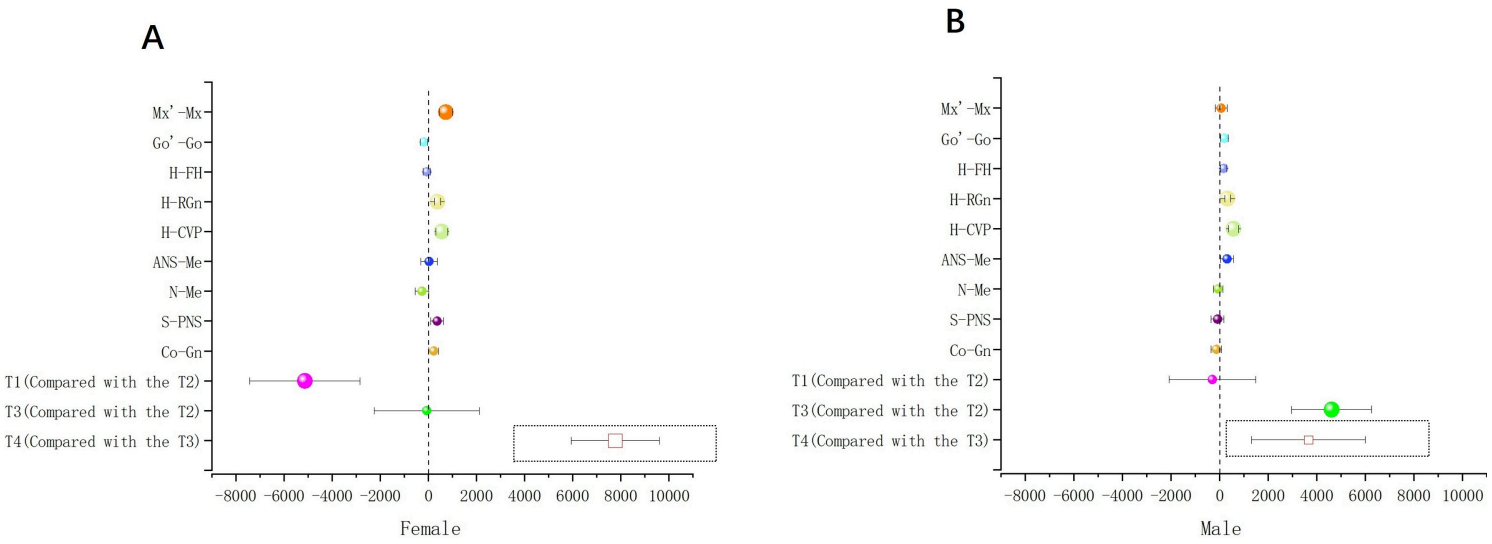


Figure 4

Forest plot of multivariable linear regression analysis.

Error bars represent ±1 standard error(SE) of the unstandardized coefficients (B). The dashed vertical line denotes the null value (B = 0). T1 and T3 estimates are with T2 as the reference; T4 estimates are with T3 as the reference (via reparameterization of the same model). Vertical boxes distinguish estimates with different reference groups.

Supplementary Files

This is a list of supplementary files associated with this preprint. Click to download.

- tables.docx