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ORIGINAL RESEARCH

Predicting OSA Using Radiographs of the Airway Anatomy

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Objective: This study aims to analyze the tongue body shape and upper airway anatomical parameters in patients with Obstructive Sleep Apnea (OSA) and to explore the anatomical causes of OSA.

Methods: A total of 345 subjects participated in this study. Lateral pharyngeal images of the upper respiratory tract were captured in both normal and mandibular advancement states using X-ray plain film. Measurements were taken for the following parameters: Tongue Length, Tongue Thickness, Distance from the Mandibular Plane to the Hyoid, Soft Palate Length, Posterior Oropharyngeal Depth, Palatal Airway Space, Tongue Depth Space, and Mental Posterior Space. The correlation between the Apnea-Hypopnea Index (AHI) and these upper airway anatomical factors was analyzed using both univariate and multivariate analyses to develop a predictive model for OSA.

Results: The anatomical structure of the upper airway in patients with OSA is narrower compared to non-OSA individuals, and these patients exhibit a longer and thicker tongue. During mandibular advancement, the pharyngeal airway widens; however, the tongue length decreases while its thickness increases. Univariate correlation analysis revealed that the severity of OSA was significantly associated with tongue length, the ratio of tongue length to tongue thickness, the distance from the mandibular plane to the hyoid, soft palate length, and body mass index (BMI) in both the normal position and during mandibular advancement ($p < 0.001$). Multivariate linear analysis indicated that the severity of OSA is linked with the mandibular plane to hyoid distance in the normal position (MPH(N)) and BMI. A nomogram was utilized to develop a predictive model for OSA, achieving an area under the receiver operating characteristic curve of 0.838.

Conclusion: The pathogenesis of OSA is related to pharyngeal anatomy and tongue length in the state of mandibular advancement, which can be predicted by the measurement indexes of normal and anterior mandibular displacement lateral pharyngeal radiograph. This may potentially aid in early screening and diagnosis of OSA.

Keywords: obstructive sleep apnea, tongue, pharyngeal radiographs, predicted model, mandibular advancement

Introduction

Obstructive Sleep Apnea (OSA) is a common disorder characterized by partial or complete obstruction of the upper airway during sleep, leading to daytime sleepiness and disruption of sleep architecture. OSA has a high incidence, with about 23–80% of the global population suffering from OSA,[1] OSA is associated with various diseases such as cardiovascular,[2] cerebrovascular,[3] various inflammatory and metabolic effects,[4–6] or cognitive dysfunction.[7] Currently, the imbalance between upper airway bone structure and soft tissue volume is considered to be the main cause of increased upper airway collapse in OSA patients.[8] Prior research indicates that the pathogenesis of OSA is intricately linked to anatomical alterations in the upper airway, including downward displacement of the hyoid bone, elongation of the soft palate, and constriction of the retropalatal space.[9,10] The tongue, being the largest anatomical structure in the

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oropharynx, is especially susceptible to enlargement caused by adipose tissue deposition.[8] Recent studies have indicated that accumulation of fat in the tongue can contribute to OSA.[11]

Currently, the assessment of upper airway morphology in OSA patients mainly includes physical examination, Müller test under laryngoscopy, head and neck X-rays, computed tomography (CT), magnetic resonance imaging (MRI) and Ultrasonic examination. In recent years, there has been a growing body of research indicating that the standard imaging techniques currently used for assessing the upper airway of OSA patients, such as X-rays,[9] CT scans,[12,13] magnetic resonance imaging (MRI)[14,15] and Ultrasonic examination[16] reveal both bony and soft tissue characteristics that may increase the risk of OSA. Shigeta et al conducted CT scans on OSA patients to assess upper airway dimensions and soft palate lengths, revealing a significant association between elongated soft palate lengths and the severity of OSA.[17] Additionally, research suggests that collapse of the lateral pharyngeal wall and upper airway length, as observed through sleep MRI, correlates with OSA severity.[15] However, despite the three-dimensional imaging capabilities of CT and MRI, their clinical utility remains limited due to economic and time constraints. Drug-induced sleep endoscopy (DISE) has emerged as a progressively utilized clinical tool; however, it necessitates sedation and carries potential risks including aspiration, laryngospasm, and profound desaturation.[8,18] Ultrasound examination is a non-invasive, radiation-free diagnostic tool that is particularly effective for visualizing soft tissues, including the soft palate, tongue base, and epiglottis. However, its utility in assessing deeper airway structures is limited by the shallow penetration of ultrasound waves and the obstruction caused by air, which impedes sound wave transmission. Moreover, ultrasound imaging is highly operator-dependent, and its accuracy may be reduced in patients with larger body sizes or in regions obscured by bony structures. However, X-ray examination has advantages of high clarity and low cost in measuring the bony structure of the upper airway. It provides efficient and clear imaging of hard tissue structures, such as the mandible and skull base, with quick imaging speed and affordable cost.

Previous research has demonstrated that individuals with OSA often exhibit pharyngeal narrowing, which necessitates contraction of the genioglossus muscle to expand the volume of the pharynx.[19–21]When patients with OSA experience mandibular advancement, the pharynx widens, potentially causing the tongue to assume a relaxed position akin to its state during sleep. Consequently, this study seeks to investigate the relationship between tongue morphology and upper airway measurements observed in lateral cephalometric X-rays of OSA patients, both in normal position and the state of mandibular advancement. The aim is to analyze the correlation between these measurements and the severity of OSA, aiming to identify anatomical indicators influencing the condition's severity.

Materials and Methods

Patients

This study was a retrospective study that included 345 subjects who underwent polysomnography at the Sleep Department of the Sixth Affiliated Hospital of Sun Yat-sen University from January 2017 to June 2020. This study was approved by the Ethics Committee of the Sixth Affiliated Hospital of Sun Yat-sen University((2021ZSLYEC-385)), and waive the requirement for informed consent.

Inclusion and Exclusion Criteria

Inclusion Criteria: (1) Age between 18 and 80 years; (2) Participants underwent a whole night of polysomnography lasting a minimum of 7 hours; (3) Participants had not received any previous treatments for sleep apnea; (4) The participants have completed lateral pharyngeal X-rays in both the normal position and the mandibular advancement position.

Exclusion Criteria: (1) History of neurological or psychiatric disorders with the potential to impact cognitive function; (2) Use of medications that could influence psychological, physiological, or respiratory control; (3) Individuals with mandibular hypoplasia or deformities; (4) Subjects lacking complete imaging and clinical documentation were excluded from the study.

Polysomnography

All enrolled patients underwent sleep monitoring. (produced by Philips Respironics, USA) to monitor the patient's overnight sleep status. The specific parameters included electroencephalogram (EEG, C4-M1, C3-M2, O2-M1, O1-M2, F4-M1, F3-M2), electrooculogram (EOG, E1-M2, E2-M2), electromyogram (EMG) of the jaw, electrocardiogram (ECG), oral and nasal airflow, chest and abdominal movements, leg movements, and oxygen saturation, etc. All PSG examinations were manually interpreted and analyzed by the same experienced sleep technician according to the American Academy of Sleep Medicine standards (AASM 2016).

Lateral Pharynx (DR) Examination

All patients included in the study underwent OSA plain film examination during calm, awake breathing states, using the same equipment for consistency. The examinations were performed separately for patients in both the normal pharyngeal lateral position and the state of mandibular advancement. During the examination, all patients were positioned sagittally without head support and instructed to remain still, refrain from swallowing, keep their mouth closed, and breathe through the nose while images were captured. All study subjects remained awake throughout the examination and underwent X-ray imaging in both the lateral pharyngeal and mandibular advancement lateral positions.

Measure

Regarding the standardization of measurement techniques, all X-ray cephalometry measurements were conducted by trained radiologists with extensive experience in airway evaluation. The cephalometric parameters (TL, TT, MPH, SP, POD, PAS, TDS, MPS) were measured following established protocols using calibrated digital X-ray equipment to ensure consistency across all patients. The measurements were repeated twice for each patient, and the mean value was used for analysis to enhance reliability. These measures were taken to reduce operator bias and improve the accuracy of our results. Using mid-sagittal plane images, measurements were taken in normal position and the state of mandibular advancement of lateral pharyngeal images:

1. Tongue Thickness (TT): The distance between the pogonion, perpendicular to the line connecting the tongue base to the anterior nasal spine (Figure 1a). TT(N): the Tongue Thickness in the state of normal body position. TT(M): the Tongue Thickness in the state of mandibular advancement.
2. Tongue Length (TL): The intersection of the line connecting the tongue base to the anterior nasal spine with the tongue shadow, measured along the line of the tongue bone (Figure 1a). TL (N): the Tongue Length in the state of normal body position. TL (M): the Tongue Length in the state of mandibular advancement.
3. Soft Palate Length (SP): Defined as the distance between the junction of the soft palate and hard palate and the lowest point of the soft palate (Figure 1a). SP (N): Soft Palate Length in the state of normal body position. SP(M): Soft Palate Length in the state of mandibular advancement.
4. Posterior Oropharyngeal Depth (POD): The distance between the tongue bone and the nearest soft tissue of the lateral pharyngeal wall (Figure 1b). POD (N): Posterior Oropharyngeal Depth in the state of normal body position. POD (M): Posterior Oropharyngeal Depth in the state of mandibular advancement.
5. Palatal Airway Space (PAS): The distance between the soft palate and the nearest soft tissue of the lateral pharyngeal wall (Figure 1b). PAS (N): Palatal Airway Space in the state of normal body position. PAS (M): Palatal Airway Space in the state of mandibular advancement.
6. Tongue Depth Space (TDS): The distance between the tongue root and the nearest soft tissue of the lateral pharyngeal wall (Figure 1b). TDS (N): Tongue Depth Space in the state of normal body position. TDS (M): Tongue Depth Space in the state of mandibular advancement.
7. Mental Posterior Space (MPS): The distance between the pogonion and the nearest soft tissue of the lateral pharyngeal wall (Figure 1b). MPS (N): Mental Posterior Space in the state of normal body position. MPS (M): Mental Posterior Space in the state of mandibular advancement.

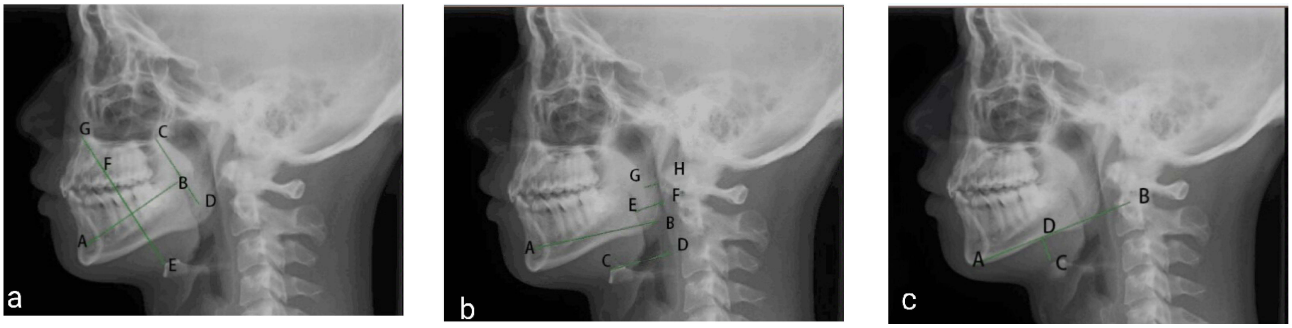

Figure 1 Measurement schematic. (**a**): AB is the distance of Tongue Thickness (TT), CD is the distance of Soft Palate Length (SP), EF is the distance of Tongue Length (TL); (**b**): AB is the distance of Mental Posterior Space (MPS), CD is the distance of Posterior Oropharyngeal Depth (POD), EF is the distance of Tongue Depth Space (TDS), GH is the distance of Palatal Airway Space (PAS); (**c**): CD is the distance of Mandibular plane to hyoid distance (MPH).

8. Mandibular plane to hyoid distance (MPH): The indicator of tongue bone position, measured from the mandibular plane to the tongue bone (Figure 1c). MPH (N): Mandibular plane to hyoid distance in the state of normal body position. (Figure 1c). MPH(M): Mandibular plane to hyoid distance in the state of mandibular advancement.
9. TT(M-N): The difference between the Tongue Thickness in the mandibular advancement state and the normal position. TL(M-N): The difference between the Tongue Length in the mandibular advancement state and the normal position. SP(M-N): The difference between the Soft Palate Length in the mandibular advancement state and the normal position. POD (M-N): The difference between the Posterior Oropharyngeal Depth in the mandibular advancement state and the normal position. MPS (M-N): The difference between the Mental Posterior Space in the mandibular advancement state and the normal position. MPH (M-N): The difference between the Mandibular plane to hyoid distance in the mandibular advancement state and the normal position.

Statistics

Data processing was conducted using SPSS 25.0 statistical software. Continuous variables were compared using *t*-tests, while categorical variables were assessed using chi-square tests. Pearson correlation analysis was utilized to explore the relationships between variables. A binary logistic regression equation was developed to construct a predictive model. The performance of the predictive model was evaluated through receiver operating characteristic (ROC) curves, calibration curves, and decision curve analysis (DCA). Sensitivity and specificity were compared. A significance level of $p \leq 0.05$ was considered statistically significant.

Result

A total of 345 subjects (55 non-OSA patients and 290 OSA patients) were included in this study. The baseline data and lateral pharyngeal radiograph measurements of the two groups of subjects (55 non-OSA and 290 OSA patients) are shown in Table 1, Supplementary Table 1 and 2. In the normal position, there were statistically significant differences in the Posterior Oropharyngeal Depth, Mandibular plane to hyoid distance, Soft Palate Length, Tongue length, Tongue thickness and Tongue length/Tongue thickness between OSA and non-OSA patients in the state of mandibular advancement, between OSA and non-OSA patients, Mandibular plane to hyoid distance, Soft Palate Length and Tongue Length and the Tongue Length/Tongue Thickness statistical differences in values.

The 290 OSA patients were further classified into mild, moderate, and severe OSA groups based on AHI. Table 2 presents the baseline characteristics and lateral pharyngeal X-ray measurements for the four groups (55 non-OSA patients and 290 OSA patients stratified by AHI). In the normal position, statistically significant differences were observed between the non-OSA group and the different severity groups in the following measurements: Mandibular plane to hyoid distance, Soft Palate Length, Tongue Length, Tongue Thickness, and Tongue Length/Tongue Thickness. In the mandibular advancement position, significant differences were found between the non-OSA group and the different OSA severity groups regarding the Mandibular plane to hyoid distance, Soft Palate Length, Tongue Length, and Tongue Length/Tongue Thickness.

Table 1 Comparison of Baseline Data and Upper Airway X-Ray Measurements Between OSA and Non-OSA Patients

Baseline Data	OSA (n=290)	Non-OSA (n=55)	p
Age	41.24±11.47	36.75±9.32	0.006
AHI	36.92±23.80	2.38±1.19	<0.001
CT90%	0.12±0.21	0	<0.001
$LSaO_2$	0.74±0.13	0.89±0.05	<0.001
Sex			<0.001
Male	254 (87.6%)	37 (67.3%)	
Female	36 (12.4%)	18 (32.7%)	
BMI	26.49±3.54	23.43±3.76	<0.001
Epworth Sleepiness Scale	8.75±5.27	8.6±5.02	0.847
MPS(N)	89.19±10.17	85.75±9.15	0.02
POD(N)	26.49±3.54	38.26±5.74	<0.001
MPH(N)	26.05±8.05	19.21±7.54	<0.001
SP(N)	49.83±6.97	45.57±6.17	<0.001
TL(N)	90.37±10.51	80.34±10.69	<0.001
TT(N)	73.9±6.42	71.83±6.15	0.028
TL(N)/TT(N)	1.23±0.16	1.12±0.14	<0.001
TDS(N)	14.34±4.97	13.58±4.4	0.291
PAS(N)	9.81±4.36	9.54±3.64	0.667
MPS(M)	99.13±11.74	95.6±10.87	0.039
POD(M)	44.06±6.24	40.4±7.15	<0.001
MPH(M)	20.55±7.89	14.85±8.14	<0.001
SP(M)	49.74±7.45	46.04±7.45	0.001
TL(M)	80.56±10.21	69.6±9.59	<0.001
TT(M)	83.54±8.14	81.69±7.69	0.12
TL(M)/TT(M)	0.98±0.3	0.85±0.11	0.002
TDS(M)	16.7±5.09	15.58±5.02	0.134
PAS(M)	10.47±3.45	10.65±3.7	0.726
MPS(M-N)	9.94±9.13	9.84±4.81	0.939
POD(M-N)	2.36±4.02	2.13±3.43	0.689
MPH(M-N)	−5.51±6.62	−4.36±5.86	0.233
SP(M-N)	−0.1±5.73	0.47±4.54	0.490
TL(M-N)	−9.81±7.88	−10.74±7.6	0.420
TT(M-N)	9.64±6.56	9.86±4.73	0.813

Abbreviations: MPS(N), Mental Posterior Space in Normal position; POD(N), Posterior Oropharyngeal Depth in Normal position; MPH(N), Mandibular plane to hyoid distance in Normal position; SP(N), Soft Palate Length in Normal position; TL(N), Tongue Length in Normal position; TT(N), Tongue Thickness in Normal position; TDS(N), Tongue Depth Space in Normal position; PAS(N), Palatal Airway Space in Normal position; MPS(M), Mental Posterior Space in mandibular advancement state; POD(M), Posterior Oropharyngeal Depth in mandibular advancement state; MPH(M), Mandibular plane to hyoid distance in mandibular advancement state; SP(M), Soft Palate Length in mandibular advancement state; TL(M), Tongue Length in mandibular advancement state; TT(M), Tongue Thickness in mandibular advancement state; TDS(M), Tongue Depth Space in mandibular advancement state; PAS(M), Palatal Airway Space in mandibular advancement state; MPS (M-N), The difference between the Mental Posterior Space in the mandibular advancement state and the normal position; POD (M-N), The difference between the Posterior Oropharyngeal Depth in the mandibular advancement state and the normal position; MPH (M-N), The difference between the Mandibular plane to hyoid distance in the mandibular advancement state and the normal position; SP(M-N), The difference between the Soft Palate Length in the mandibular advancement state and the normal position; TL(M-N), The difference between the Tongue Length in the mandibular advancement state and the normal position; TT(M-N), The difference between the Tongue Thickness in the mandibular advancement state and the normal position; AHI, Apnea hypopnea index; LSaO2, minimum blood oxygen saturation; CT90%, Percentage of total sleep time with blood oxygen saturation below 90%.

Table 2 Comparison of Baseline Data and Upper Airway X-Ray Measurements Between Non-OSA and OSA Patients Stratified by AHI

Baseline Data	Non-OSA (n=55)	Mild OSA (n=64)	Moderate OSA (n=71)	Severe OSA (n=155)	p
Age	36.75±9.32	40.31±13.19	40.70±10.92	41.88±10.91	0.037
Sex					<0.001
Male	37 (67.3%)	51 (79.7%)	60 (84.5%)	143 (92.26%)	
Female	18 (32.7%)	13 (20.3%)	11 (15.5%)	12 (7.74%)	
BMI	23.43±3.76	24.46±2.6	25.9±3.45	27.6±3.51	<0.001
Epworth Sleepiness Scale	8.6±5.02	8±5.2	8.01±5.23	9.4±5.27	0.164
MPS(N)	85.75±9.15	86.16±10.32	88.79±7.41	90.63±10.94	0.002
POD(N)	38.26±5.74	39.84±5.52	41.21±5.03	42.67±5.68	<0.001
MPH(N)	19.21±7.54	22.63±6.29	23.94±6.75	28.43±8.5	<0.001
SP(N)	45.57±6.17	47.6±6.46	48.02±6.14	51.58±7.09	<0.001
TL(N)	80.34±10.69	86.18±9.47	87.78±8.48	93.28±10.9	<0.001
TT(N)	71.83±6.15	72.88±5.32	73.41±5.76	74.55±7.04	0.037
TL(N)/TT(N)	1.12±0.14	1.19±0.14	1.2±0.13	1.26±0.17	<0.001
TDS(N)	13.58±4.4	14.38±5.15	14.22±5.24	14.39±4.8	0.759
PAS(N)	9.54±3.64	9.85±2.92	9.32±4.16	10.01±4.92	0.691
MPS(M)	95.6±10.87	96.69±11.19	99.78±8.95	99.84±12.96	0.049
POD(M)	40.4±7.15	42.53±5.26	43.78±6.07	44.81±6.6	<0.001
MPH(M)	14.58±8.14	17.3±6.88	19.46±7.33	22.38±8.04	<0.001
SP(M)	46.04±7.45	47.51±7.79	48.47±6.36	51.23±7.48	<0.001
TL(M)	69.6±9.59	75.92±9.32	78.08±8.54	83.61±10.29	<0.001
TT(M)	81.69±7.69	83.42±5.8	82.75±10.77	83.9±7.59	0.318
TL(M)/TT(M)	0.85±0.11	0.91±0.11	1±0.55	1±0.13	0.002
TDS(M)	15.58±5.02	16.33±5.17	16.27±4.69	17.04±5.25	0.283
PAS(M)	10.65±3.7	10.57±3.45	10.15±3.43	10.58±3.48	0.815
MPS(M-N)	9.84±4.81	10.53±6.5	10.98±5.11	9.22±11.23	0.485
POD(M-N)	2.13±3.43	2.69±4.76	2.56±3.88	2.14±3.76	0.736
MPH(M-N)	−4.36±5.86	−5.33±7.15	−4.48±6.33	−6.05±6.5	0.231
SP(M-N)	0.47±4.54	−0.1±6.07	0.45±4.37	−0.35±6.13	0.648
TL(M-N)	−10.74±7.6	−10.26±7.71	−9.7±7.25	−9.67±8.27	0.821
TT(M-N)	9.86±4.73	10.53±4.54	9.35±9.85	9.41±5.27	0.636

Abbreviations: MPS(N), Mental Posterior Space in Normal position; POD(N), Posterior Oropharyngeal Depth in Normal position; MPH(N), Mandibular plane to hyoid distance in Normal position; SP(N), Soft Palate Length in Normal position; TL(N), Tongue Length in Normal position; TT(N), Tongue Thickness in Normal position; TDS(N), Tongue Depth Space in Normal position; PAS(N), Palatal Airway Space in Normal position; MPS(M), Mental Posterior Space in mandibular advancement state; POD(M), Posterior Oropharyngeal Depth in mandibular advancement state; MPH(M), Mandibular plane to hyoid distance in mandibular advancement state; SP(M), Soft Palate Length in mandibular advancement state; TL(M), Tongue Length in mandibular advancement state; TT(M), Tongue Thickness in mandibular advancement state; TDS(M), Tongue Depth Space in mandibular advancement state; PAS(M), Palatal Airway Space in mandibular advancement state; MPS (M-N), The difference between the Mental Posterior Space in the mandibular advancement state and the normal position; POD (M-N), The difference between the Posterior Oropharyngeal Depth in the mandibular advancement state and the normal position; MPH (M-N), The difference between the Mandibular plane to hyoid distance in the mandibular advancement state and the normal position; SP(M-N), The difference between the Soft Palate Length in the mandibular advancement state and the normal position; TL(M-N), The difference between the Tongue Length in the mandibular advancement state and the normal position; TT(M-N), The difference between the Tongue Thickness in the mandibular advancement state and the normal position; Non-OSA, AHI < 5; Mild OSA, 5 ≤ AHI < 15; Moderate OSA, 15 ≤ AHI < 30; Severe OSA, AHI ≥ 30; AHI, Apnea hypopnea index; $LSaO_2$, minimum blood oxygen saturation; CT90%, Percentage of total sleep time with blood oxygen saturation below 90%.

Table 3 presents a comparison of upper airway X-ray measurements between the normal position and mandibular advancement in 345 subjects included in the study. When in the anterior displacement of the mandible, the tongue length becomes shorter, the tongue thickness becomes larger and the pharyngeal airway becomes wider.

Table 4 and Figure 2 show the correlation analysis of OSA severity (AHI, $LSaO_2$, CT90%) with clinical features and imaging measurements. The severity of OSA patients was significantly correlated with BMI/ (Kg M-2), MPS(N),

Table 3 Comparison of Baseline and Upper Airway X-Ray Measurements Between Two Groups

	Pharyngeal Lateral View (n=345)	Mandibular Advancement Lateral View (n=345)	p
TL	88.77±11.14	78.81±10.87	<0.01
MPH	24.96±8.35	19.64±8.19	<0.01
SP	49.15±7.01	49.15±7.56	0.983
TT	73.57±6.41	83.25±8.09	<0.01
TDS	14.22±4.89	16.52±5.09	<0.01
POD	9.77±4.25	10.50±3.49	<0.01
MPS	88.64±10.08	98.57±11.66	<0.01

Abbreviations: TL, Tongue Length; MPH, Mandibular plane to hyoid distance; SP, Soft Palate Length; TT, Tongue Thickness; TDS, Tongue Depth Space; POD, Posterior Oropharyngeal Depth; MPS, Mental Posterior Space.

POD(N), MPH(N), SP(N), TL(N), MPH(m), SP(M), TL(M) and TL(M)/TT(M). The ratio of tongue length to tongue thickness increased with the severity of OSA.

Multivariate linear analysis showed that OSA severity (AHI, LSaO2, CT90%) was correlated with MPH(N) and BMI, as shown in Table 5.

The 345 people included in the study were divided into non-OSA group (n=55) and OSA group (n=290) according to the AHI value. Binary logistic regression analysis showed that OSA was correlated with MPH(N), TL(M) and BMI (Table 6). A nomogram prediction model was established using MPH(N), TL(M) and BMI, as shown in Figure 3. The area under the curve of the prediction model was 0.838 and the decision curve and calibration curve are shown in Figure 4.

Discussion

In this study, we used the mandibular advancement in lateral pharyngeal radiograph combined with the normal position in lateral pharyngeal radiograph to evaluate the pharyngeal condition of OSA patients. It was found that OSA was related to the hyoid bone height in the normal position and the tongue length in the mandibular advancement, which was helpful to help the diagnosis of OSA patients and provide guidance for the treatment of OSA. To the best of our knowledge, this is the first study to evaluate the pharyngeal anatomy as well as tongue morphology in OSA patients using lateral pharyngeal radiographs with combined anterior mandibular displacement.

This study found that patients with OSA normal position, the tongue shape oval (length/thickness of about 1.23), and lower jaw forward position, tongue shape close to round (length/thickness of about 0.98). Previous studies have found that genioglossus EMG potential in OSA patients is higher than that in normal people,[22] which increases the volume of retroglossal space and maintains the patency of the upper airway through tongue muscle contraction. However, in the state of mandibular advancement, the cross-sectional area of the pharyngeal cavity expands and the tongue muscles relax, which leads to the change of tongue morphology.[23] Therefore, the tongue morphology during anterior mandibular displacement may be used to predict the tongue morphology during sleep in OSA patients when the tongue is relaxed, and to predict the effect of the mandibular advancement device in the treatment of OSA. The next step is imaging during induced sleep.

Our results revealed a positive correlation between OSA severity and BMI. Additionally, in the normal position, OSA patients exhibited significantly longer soft palates compared to the control group, consistent with previous findings.[24] This suggests that the soft palate may be a vulnerable area for airway collapse, exacerbating obstruction in multiple regions, including the posterior tongue area.[25] The results of this study indicate that in the OSA group, the mean distance between the hyoid bone and the mandibular plane, known as the hyoid bone height, was 26.05 ±8.05 in the normal pharyngeal lateral position, and 20.55±7.89 in the mandibular advancement position. From these data, it can be observed that mandibular advancement altered some cephalometric features of the subjects, significantly reducing the position of

Table 4 Association Between Baseline Data, Upper Airway X-Ray Positivity and Mandibular Anterior Displacement Measurements and Disease Severity in OSA Patients

Measurement Parameter	rAHI	pAHI	rLSaO$_2$	p LSaO$_2$	rCT90%	pCT90%
Age	0.055	0.351	−0.096	0.104	0.074	0.212
BMI/ (Kg m-2)	0.436	<0.001	−0.377	<0.001	0.398	<0.001
MPS(N)	0.19	0.001	−0.167	0.004	0.161	0.006
POD(N)	0.242	<0.001	−0.166	0.005	0.170	0.004
MPH(N)	0.336	<0.001	−0.279	<0.001	0.30	<0.001
SP(N)	0.282	<0.001	−0.269	<0.001	0.209	<0.001
TL(N)	0.355	<0.001	−0.269	<0.001	0.257	<0.001
TT(N)	0.106	0.07	−0.054	0.357	0.096	0.104
TL(N)/TT(N)	0.236	<0.001	−0.189	0.001	0.148	0.012
TDS(N)	0.082	0.161	−0.077	0.194	0.077	0.191
PAS(N)	−0.022	0.713	0.017	0.777	−0.012	0.840
MPS(M)	0.131	0.026	−0.059	0.321	0.092	0.120
POD(M)	0.185	0.002	−0.084	0.156	0.088	0.134
MPH(M)	0.283	<0.001	−0.232	<0.001	0.232	<0.001
SP(M)	0.274	<0.001	−0.233	<0.001	0.209	<0.001
TL(M)	0.394	<0.001	−0.304	<0.001	0.273	<0.001
TT(M)	0.082	0.165	0.006	0.925	0.055	0.353
TL(M)/TT(M)	0.312	<0.001	−0.253	<0.001	0.198	0.001
TDS(M)	0.075	0.202	−0.079	0.179	0.069	0.246
PAS(M)	−0.019	0.751	0.007	0.905	−0.026	0.665
MPS(M-N)	−0.075	0.203	0.108	0.067	−0.089	0.131
POD(M-N)	−0.032	0.587	0.075	0.201	−0.086	0.146
MPH(M-N)	−0.068	0.249	0.054	0.359	−0.071	0.230
SP(M-N)	−0.008	0.890	0.005	0.932	0.015	0.798
TL(M-N)	0.004	0.942	−0.016	0.785	−0.028	0.640
TT(M-N)	−0.052	0.374	0.083	0.160	−0.066	0.266

Abbreviations: MPS(N), Mental Posterior Space in Normal position; POD(N), Posterior Oropharyngeal Depth in Normal position; MPH(N), Mandibular plane to hyoid distance in Normal position; SP(N), Soft Palate Length in Normal position; TL(N), Tongue Length in Normal position; TT(N), Tongue Thickness in Normal position; TDS(N), Tongue Depth Space in Normal position; PAS(N), Palatal Airway Space in Normal position; MPS(M), Mental Posterior Space in mandibular advancement state; POD(M), Posterior Oropharyngeal Depth in mandibular advancement state; MPH(M), Mandibular plane to hyoid distance in mandibular advancement state; SP(M), Soft Palate Length in mandibular advancement state; TL(M), Tongue Length in mandibular advancement state; TT(M), Tongue Thickness in mandibular advancement state; TDS(M), Tongue Depth Space in mandibular advancement state; PAS(M), Palatal Airway Space in mandibular advancement state; MPS (M-N), The difference between the Mental Posterior Space in the mandibular advancement state and the normal position; POD (M-N), The difference between the Posterior Oropharyngeal Depth in the mandibular advancement state and the normal position; MPH (M-N), The difference between the Mandibular plane to hyoid distance in the mandibular advancement state and the normal position; SP (M-N), The difference between the Soft Palate Length in the mandibular advancement state and the normal position; TL(M-N), The difference between the Tongue Length in the mandibular advancement state and the normal position; TT(M-N), The difference between the Tongue Thickness in the mandibular advancement state and the normal position.; OSA, Obstructive sleep apnea; BMI, body mass index; AHI, Apnea hypopnea index; LSaO$_2$, minimum blood oxygen saturation; CT90%, Percentage of total sleep time with blood oxygen saturation below 90%.

the hyoid bone relative to the mandible. Additionally, the distance from the mandibular plane to the hyoid bone was significantly correlated with the severity of OSA, consistent with similar findings in the literature.[10,26] Past studies[27,28] have attributed this phenomenon to the forward movement of the mandible, which pulls the muscles attached to the hyoid bone forward, thereby reducing the distance between the hyoid bone and the mandibular plane, leading to improved airway patency. However, the difference between the Mandibular plane to hyoid distance in the mandibular advancement state and the normal position between mandibular advancement and normal sagittal positions did not reach statistical significance.

Previous studies have shown that the lowest oxygen saturation is associated with tongue volume.[29] In our study, univariate analysis found that OSA severity was associated with tongue length and tongue thickness in both positions.

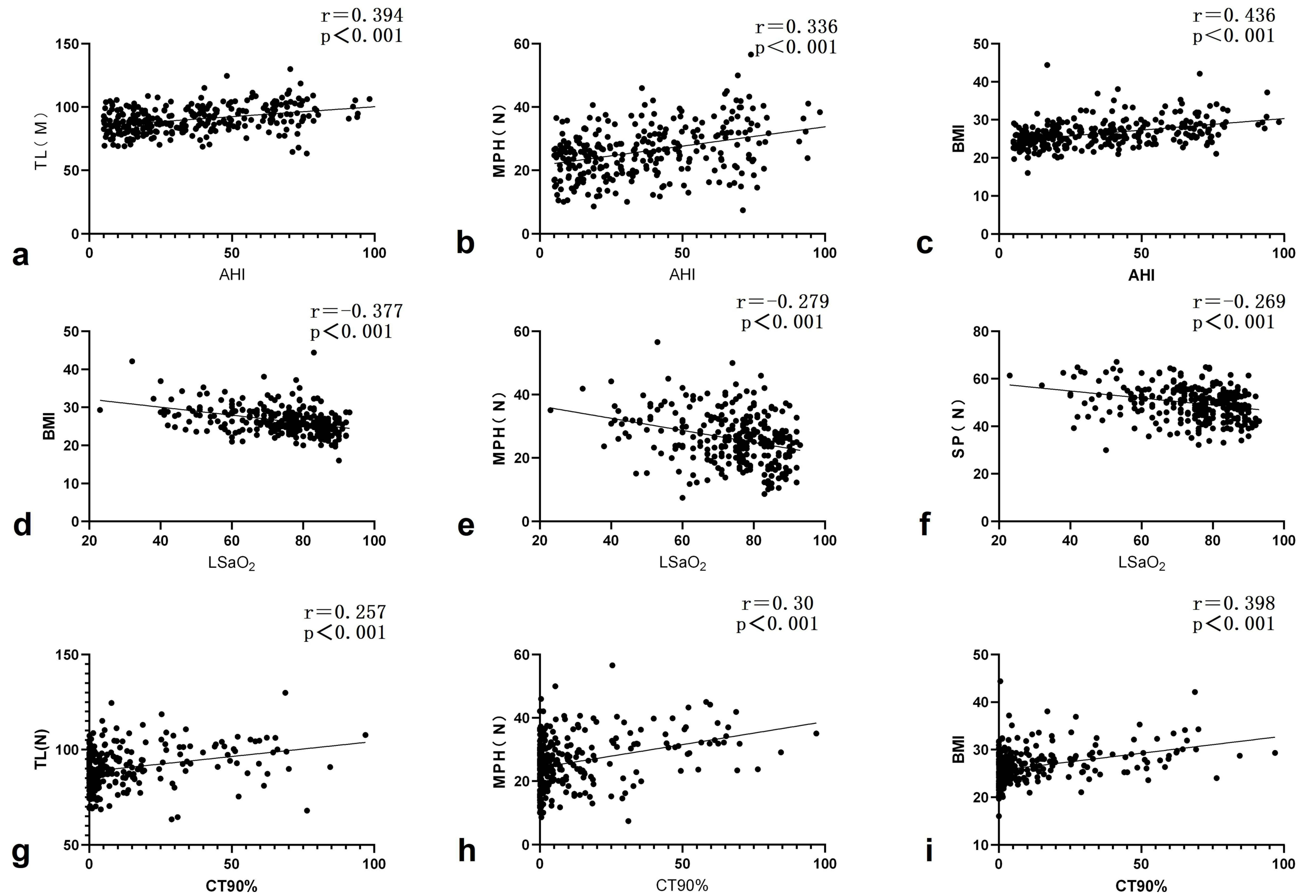

Figure 2 Linear regression analysis between AHI, LSaO2, CT90% and measured values ((**a**) Correlation between TL(M) and AHI (r=0.394, p<0.001); (**b**) Correlation between MPH(N) and AHI (r=0.336, p<0.001); (**c**) Correlation between BMI and AHI (r=0.436, p<0.001); (**d**) Correlation between BMI and $LSaO_2$ (r=−0.377, p<0.001); (**e**) Correlation between MPH(N) and $LSaO_2$ (r=−0.279, p<0.001); (**f**) Correlation between SP(N) and $LSaO_2$ (r=−0.269, p<0.001); (**g**) Correlation between TL(N) and CT90% (r=0.257, p<0.001); (**h**) Correlation between MPH(N) and CT90% (r=0.30, p<0.001); (**i**) Correlation between BMI and CT90% (r=0.398, p<0.001)).
Abbreviations: TL (M), the Tongue Length in mandibular advancement state; MPH (N), Mandibular plane to hyoid distance in Normal position; BMI, Body Mass Index; SP (N), Soft Palate Length in Normal position; TL (N), the Tongue Length in Normal position; AHI, Apnea hypopnea index; LSao2, minimum blood oxygen saturation; CT90%, Percentage of total sleep time with blood oxygen saturation below 90%.

Multivariate analysis showed that tongue length and tongue thickness were not associated with lowest oxygen saturation. Only AHI was associated with tongue length in the mandibular advancement. This may be because hyoid height is correlated with tongue length and tongue thickness; therefore, in the multivariate analysis, the lowest oxygen saturation was not correlated with tongue measurements when collinear thickness was removed.

In the evaluation of airway parameters of obstructive sleep apnea (OSA), X-ray cephalometry, ultrasonography, CT and MRI have their unique advantages and limitations. X-ray skull measurements, such as SNA, SNB, ANB, NSBA, and MPH, provide detailed bone markers that are critical for assessing craniofacial structures associated with airway space. X-ray imaging is readily available, cost-effective, and provides consistent results for bone evaluation. However, its limitation lies in its two-dimensional nature, which limits its ability to evaluate the soft tissue structure and dynamic properties of the upper respiratory tract. Ultrasound, on the other hand, offers a non-invasive, non-radiative alternative that performs well in visualizing soft tissues, especially in areas such as the soft palate, oropharynx, base of the tongue, and epiglottis. Recent studies, including the work of Terawatpothong A et al have demonstrated a significant correlation between head measurement parameters in these areas and ultrasound measurements, highlighting the complementary role of ultrasound in airway assessment. Ultrasound also allows for real-time imaging, making it particularly useful when assessing dynamic airway changes during breathing or jaw progression. However, ultrasound may depend on the operator and its accuracy may be limited in larger patients or in areas obscured by bone structures. Thus, while X-ray cephalometry remains a valuable initial bone assessment tool, ultrasound provides added value in soft tissue assessment

Table 5 Associations Between AHI, CT90, or Minimum Oxygen Saturation Levels and Baseline Data and Upper Airway X-Ray Measurements Were Analyzed by Linear Regression

	Independent Variable	B±SE	p
AHI	TL(M)	0.410±0.144	0.005
	MPH(N)	0.589±0.178	0.001
	BMI	2.063±0.361	<0.01
$LSaO_2$	SP(N)	−0.225±0.107	0.035
	MPH(N)	−0.333±0.090	<0.01
	BMI	−1.108±0.205	<0.01
CT90%	POD(M-N)	−0.604±0.277	<0.01
	MPH(N)	0.572±0.141	<0.01
	BMI	1.667±0.322	<0.01

Abbreviations: TL(M), Tongue Length in mandibular advancement state; MPH(N), Mandibular plane to hyoid distance in Normal position; SP(N), Soft Palate Length in Normal position; MPH(N), Mandibular plane to hyoid distance in Normal position; POD (M-N), The difference between the Posterior Oropharyngeal Depth in the mandibular advancement state and the normal position; BMI, body mass index; AHI, Apnea hypopnea index; LSao2, minimum blood oxygen saturation; CT90%, Percentage of total sleep time with blood oxygen saturation below 90%.

Table 6 Binary Logistic Regression Analysis Between OSA and Non-OSA Groups

Measurement Parameter	B	SE	Wald X^2	p
MPH(N)	0.08	0.028	7.846	0.005
TL(M)	0.075	0.021	13.126	0
BMI	0.227	0.058	15.229	0
constant	−11.341	1.937	34.298	0

Abbreviations: MPH(N), Mandibular plane to hyoid distance in Normal position; TL(M), Tongue Length in mandibular advancement state; BMI, body mass index.

and dynamic assessment. Terawatpothong A et al believe that the combination of the two approaches can provide a more comprehensive understanding of airway morphology in patients at high risk for OSA.[30]

CT imaging provides superior spatial resolution and three-dimensional visualization of the airway structure, allowing for a more comprehensive assessment of bone and soft tissue components. In particular, for patients with low but normal

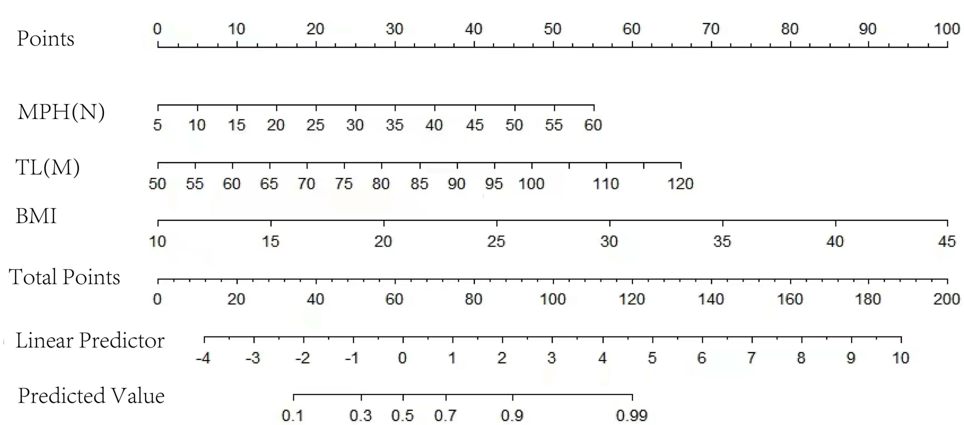

Figure 3 Nomogram for the diagnosis of OSA.
Abbreviations: MPH (N), the Tongue Thickness in the state of normal body position; TL(M), Tongue Length in mandibular advancement state; BMI, body mass index.

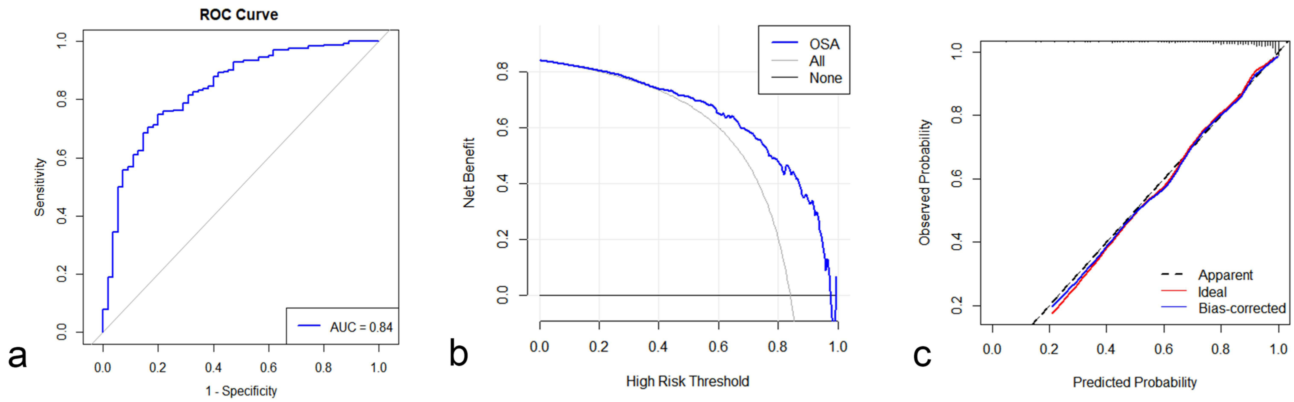

Figure 4 The ROC curve, decision curve and the calibration curve of OSA prediction model. (**a**). the ROC curve of the model and the AUC= 0.84; (**b**). the decision curve of the model; (**c**). the calibration curve of the model.

airway space parameters on X-rays, CT can provide additional diagnostic value, especially when performed in a supine position that more closely mimics the natural state during sleep. However, compared to X-rays, CT is more expensive, involves higher radiation exposure, and is not readily available in a routine clinical setting. Therefore, it should be considered when more accurate airway analysis is required or X-ray results are uncertain. Taking these factors into account, a balanced approach that utilizes X-rays for initial screening and retains CT for cases requiring more detailed evaluation will optimize clinical utility and resource utilization. This view is consistent with the findings of Meisgeier A et al who highlighted the added value of 3D imaging in assessing spatial stenosis of the upper airway.[31]

MRI has significant advantages in soft tissue imaging, and can clearly show the anatomical structures such as the soft palate, the base of the tongue and the oropharynx. MRI provides high-resolution three-dimensional images and supports dynamic imaging that can observe functional collapse areas of the upper airway while the patient is sleeping, helping to identify multiple layers of obstruction. But MRI is usually more expensive and takes longer to scan, which can cause discomfort for some patients. In contrast, X-ray is low-cost, convenient to operate, and suitable for routine preliminary screening and evaluation of bone structure. X-ray is effective in the evaluation of craniofacial bone structure, especially for the measurement of bone markers (such as SNA, SNB, etc.), which can provide detailed information about craniofacial bone structure for OSA patients, while MRI is usually inferior to X-ray in this respect.

Our study has several potential limitations. First of all, Among the 345 participants retrospectively included, only 55 were non-OSA patients, as it is rare for individuals without OSA to visit the hospital specifically for lateral pharyngeal radiographs. Also, age and BMI were not matched between the two groups. Our predictive models were adjusted for these variables to mitigate their impact, though they were not directly matched by age and BMI. This imbalance may impact the predictive performance of our model and the findings may not be generalizable to all populations. Second, our study used pharyngeal radiographs, which cannot measure volume and may be less accurate in measuring soft tissues than CT or MRI. In addition, although we applied an innovative approach to examine the movement of soft tissue structures, this is an oversimplification of anatomical changes in soft tissue, including changes in the morphology of individual structures. Other methods to assess these subtle changes, such as finite element analysis, may be necessary to quantify these differences.

Conclusion

The pathogenesis of OSA is related to pharyngeal anatomy and tongue length in the state of mandibular advancement, which can be predicted by the measurement indexes of normal and anterior mandibular displacement lateral pharyngeal radiograph. This may potentially aid in early screening and diagnosis of OSA.

Ethical Approval and Consent to Participate

This study involved a retrospective analysis of existing patient records, approved by the Ethics Committee of the Sixth Affiliated Hospital of Sun Yat-sen University. We conducted the study in accordance with the principles outlined in the Declaration of Helsinki. We confirm that all data collection and analysis adhered to ethical standards and guidelines, ensuring the integrity of the research process while safeguarding the rights and welfare of the patients.

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Disclosure

The authors report no conflicts of interest in this work.

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