ORIGINAL ARTICLE

Relationship Between Anterior Cranial Base Morphology and Airway Volume Measured on CBCT Scans: A Cross-Sectional Study

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ABSTRACT

Objective: To investigate the relationship between anterior cranial base morphology and pharyngeal airway dimensions, including total airway volume, compartmental volumes, and minimum cross-sectional area.

Study Design: A cross-sectional study.

Place and Duration of Study: This study was conducted at the Department of Orthodontics and Oral & Maxillofacial Surgery at the Dental College, HITEC-IMS, Taxila, Pakistan, from January 2025 to January 2026.

Methods: We included 193 patients aged 8 to 18 years, selected through non-probability sequential sampling, who had available Cone-Beam Computed Tomography (CBCT) scans. Those with respiratory pathologies, craniofacial syndromes, or systemic illness were left out. 3D cephalometric landmarks were plotted using Planmeca Romexis software. ACBL was recorded as the Sella-Nasion distance; ACBI was the angle this line made with the true horizontal. Retropalatal and retroglossal airway volumes plus CSA min were then computed. Multiple linear regression and partial correlation analyses were applied, controlling for age and sex, with a significance threshold of $P < 0.05$.

Results: ACBI averaged 8.62 ± 2.65 degrees; ACBL, 65.60 ± 3.52 mm. Mean airway volume was 13,470.89 ± 4,259.86 mm^3. The minimum cross-sectional area averaged 63.67 ± 33.06 mm^2. ACBL showed a weak positive correlation with total airway volume ($r = 0.202$, $P = 0.006$) as well as CSA min ($r = 0.334$, $P < 0.001$). No significant association emerged between ACBI and airway volume ($r = 0.028$, $P = 0.69$) or CSA min ($r = 0.019$, $P = 0.796$).

Conclusion: In this study, patients with longer ACBL had greater airway volumes and wider CSA min. whereas the tilt of the anterior cranial base made no measurable difference to any airway variable examined.

Keywords: *Airway Obstruction, Cone-Beam Computed Tomography, Growth, Malocclusion, Oropharynx, Pharynx.*

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Introduction

Most people are never aware of breathing until it becomes difficult. For nasal respiration to work properly, the pharyngeal space enclosed within the craniofacial skeleton must remain patent. When it does not, the consequences can ripple outward in ways that extend well beyond simple discomfort.[1] From orthodontic malocclusion to sleep-disordered breathing, a compromised airway can change how the face grows and how the body functions.[2]

The cranial base, mandible, hyoid bone, and cervical spine all work together in harmony to make the skeletal envelope of the pharynx, in which the soft tissues of the airway must operate.[3] The airway may become constricted if this bony scaffold is small or poorly formed. Obstruction need not be dramatic to cause problems. Even partial narrowing triggers a switch from nasal to oral breathing, and the body compensates through a characteristic postural triad — the head extends forward, the tongue drops anteriorly, and the mandible shifts downward.[4] Over months and years in a growing child, these compensations reshape the face. The clinical endpoint is often a long-face morphology with Class II skeletal tendency, a short and downwards rotated

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mandible which restricts the oropharynx, whose anterior wall is primarily comprised of the soft palate, tongue, and lingual tonsils; these might cause constriction and narrowing of the airway leading to a far more serious diagnosis of obstructive sleep apnea (OSA).[5,6]

OSA, especially in children and adolescents, is not a harmless condition. Literature has linked it to attention deficit hyperactivity disorder, elevated blood pressure, poor academic performance, and, in severe or untreated cases, right-sided heart strain.[7] Clearly, identifying at-risk individuals before the airway problem becomes entrenched, especially in children and adolescents, is a priority for any clinician managing growing patients.

The anterior cranial base, measured from Sella to Nasion (ACBL), and its angular tilt relative to the true horizontal plane (ACBI) are noteworthy because this structure completes the bulk of its growth by around eight years of age.[8] After that, it remains remarkably stable — making it, at least in theory, a dependable skeletal reference point.[9] If ACBL or ACBI can predict something about how much room the airway has, clinicians would gain a useful screening parameter available on any CBCT that already includes the cranial base field of view.

CBCT technology has a revolutionary role in the assessment and advanced management of airway-related conditions. Two-dimensional cephalograms will give you a flat image, which will not contain the important, useful volumetric values.[10] CBCT has overcome these limitations. It permits calculation of total airway volume, compartment-specific volumes for the retropalatal and retroglossal spaces, and — perhaps most importantly — the minimum cross-sectional area (CSA min), which represents the tightest bottleneck in the airway.[11,12]

Few studies have used three-dimensional imaging to clinically link cranial base form to airway size, and even fewer have done so in Pakistan.[13] Due to their different cranial shape, East Asian and Caucasian literature is more abundant than South Asian literature.[14] Thus, population-specific data is essential. With this background, we set out to investigate whether ACBL and ACBI show any measurable correlation with airway volume and CSA min on CBCT scans in patients aged 8 to 18 years reporting to our institution.

Methods

This cross-sectional study was conducted in the Departments of Orthodontics and Oral & Maxillofacial Surgery at the Dental College HITEC-IMS, Taxila, Pakistan, from January 2025 to January 2026. Ethical approval was obtained from the Institutional Review Board of the institute, vide letter no: Dental/IRB/75, dated: 09th October 2024. Prior to commencement of the study. After obtaining written informed consent from each participant or the parent/guardian of minors, the study data were accessed.

Sample size estimation was performed on G*Power version 3.1.9.4.[15] We set alpha at 0.05, power at 0.80, and used a conservative anticipated correlation coefficient of $r = 0.20$ drawn from earlier published work.[3,4] This yielded a minimum requirement of 193 subjects. Using non-probability sequential sampling, we recruited individuals who had been prescribed CBCT scans for routine clinical purposes and were already attending outpatient clinics.

Inclusion Criteria: Any patient ranging between eight and eighteen years of age and undergoing CBCT scans, regardless of the indication, was selected for this study.

Exclusion Criteria: Any participant having tonsillar or adenoid enlargement, or any other respiratory tract abnormality, was not selected. Further parameters for non-selection included active allergic disease, neuromuscular disorder, any respiratory disease, or any craniofacial syndrome. In terms of imaging, CBCT scans were rejected due to motion artifacts, inadequate field of view, improper airway recording, or scanning parameters that deviated from departmental standards.

A 3D unit of Planmeca Promax was utilized for scans and imagery. Additionally, all scans were acquired at 8 mA , 70 kVp and a 2-in field of view setting. Each patient's image data consisted of 512 slices, with a thickness of 0.3mm, a resolution of 1024x1024 pixels, and 12 bits per pixel. Scans were taken with the patients seated upright, in natural head posture, with teeth in maximum intercuspation and the tongue resting against the palate. Maintaining a standardized posture was important because even minor forward or backward tilting of the head has been shown to alter pharyngeal airway dimensions on CBCT.[16]

The Planmeca Romexis program (version 6.2) was used for measurements and reconstructions. To standardize the three-dimensional orientation, three reference planes were defined. First, the midsagittal plane was created. It was defined using three anatomic landmarks.

These landmarks were Sella (S), Nasion (N), and Basion (Ba). Next, an axial reference was drawn at right angles to the midsagittal plane, running through both N and S. A coronal reference was then set through Sella, kept perpendicular to the two planes already established. The intersection of the three planes at Sella served as the origin of the coordinate system. On every scan, the following eight cephalometric landmarks were located and digitized: Sella turcica, Nasion, ANS, PNS, condylion, gnathion, gonion, and menton.

We recorded ACBL as the linear S–N distance in millimeters. The angle formed by the S-N line and the actual horizontal plane was used to calculate ACBI. It was measured in degrees. For airway evaluation in the sagittal view, specific limits were defined. A horizontal line running across the PNS was the upper border.

A horizontal line that touched the epiglottis's highest point served as the bottom limit. A third horizontal line through the uvula tip divided this space into a retropalatal compartment above and a retroglossal compartment below. Using the built-in volumetric tools in Romexis, we computed the volume of each compartment, the total airway volume, the average cross-sectional area of each compartment, and the CSA min — the single smallest cross-section along the entire airway column.

All statistical work was carried out in SPSS 24.0. We expressed continuous variables as their mean ± SD. A multiple linear regression analysis was applied to check the effects of gender, age, anterior cranial base length (ACBL), and anterior cranial base inclination (ACBI) on total airway volume and minimum cross-sectional area (CSA min). We then proceeded with partial correlation analysis, controlling for age and sex. We set our significance cut-off at $P < 0.05$ for every test

For reproducibility checks, 20 scans were selected randomly and had the same examiner re measure them 2 weeks later. Intra class correlation coefficients were above 0.90 for all linear and volumetric variables, which we considered satisfactory intra-examiner consistency. We felt this verification was warranted, given that volumetric airway segmentation on CBCT is sensitive to operator-selected thresholds; knowing that our protocol yielded repeatable measurements across sessions added confidence in the dataset.[1,12]

Results

Of the 193 CBCT records that met our criteria, 86 belonged to male patients (44.6%) and 107 to female patients (55.4%). Mean age was 13.1 years with a SD of ±3.16. Table 1 lays out the descriptive statistics.

When the data were split by sex, males showed a cranial base averaging 66.37 ± 3.29 mm, about a millimeter and a half longer than the 64.97 ± 3.59 mm recorded for females. Airway volume differed by approximately 2,768 mm³ between the sexes (males averaged 15005.78 ± 3978.04 mm³ and females 12237.25 ± 4090.43 mm³).

Multiple linear regression analyses were performed to evaluate the effects of gender, age, anterior cranial base length (ACBL), and anterior cranial base inclination (ACBI) on total airway volume and minimum cross-sectional area (CSA min).

Table 1: Descriptive Parameters of Study Variables (N = 193)

Variable	N	Mean	SD	Min	Max
ACBL (mm)	193	65.60	3.52	55.0	75.8
ACBI (degrees)	193	8.62	2.65	2.3	16.4
Total Airway Volume (mm³)	193	13470.89	4259.86	5057.5	27427.1
Retropalatal Volume (mm³)	193	7983.91	2609.54	2782.3	16737.5
Retroglossal Volume (mm³)	193	5486.99	1754.78	1898.3	12324.3
CSA min (mm²)	193	63.67	33.06	20.0	191.3

ACBL: Anterior Cranial Base Length; ACBI: Anterior Cranial Base Inclination; CSA min: Minimum Cross-Sectional Area

Table 2: Partial Correlation Between Anterior Cranial Base Parameters and Airway Measurements

Cranial Base Parameter	Airway Variable	Partial r	*P*-value
ACBL (mm)	Total Airway Volume (mm³)	0.202	0.006
	CSA min (mm²)	0.334	<0.001
	Retropalatal Volume (mm³)	0.225	0.002
	Retroglossal Volume (mm³)	0.144	0.047
ACBI (degrees)	Total Airway Volume (mm³)	0.028	0.69
	CSA min (mm²)	0.019	0.796
	Retropalatal Volume (mm³)	0.038	0.602
	Retroglossal Volume (mm³)	0.011	0.876

ACBL: Anterior Cranial Base Length; ACBI: Anterior Cranial Base Inclination; CSA min: Minimum Cross-Sectional Area

For total airway volume, the overall regression model was statistically significant (**F**(4, 188) = 36.93, $P < 0.001$), explaining 44.0% of the variance ($R^2 = 0.440$; adjusted $R^2 = 0.428$). Age ($\beta = 0.493$, $P < 0.001$) and ACBL ($\beta = 0.175$, $P = 0.005$) were significant positive predictors, whereas gender was a significant negative predictor ($\beta = -0.283$, $P < 0.001$). ACBI was not significantly associated with total airway volume ($P = 0.573$).

Similarly, the regression model for CSA min was significant (4, 188) = 19.92, $P < 0.001$), accounting for 29.8% of the variance ($R^2 = 0.298$; adjusted $R^2 = 0.283$). Gender ($\beta = -0.202$, $p = 0.002$), age ($\beta = 0.226$, $P = 0.001$), and ACBL ($\beta = 0.339$, $P < 0.001$) were significant predictors, while ACBI was not ($P = 0.575$). Multicollinearity was not evident (VIF = 1.018–1.288), and the Durbin–Watson statistics (2.048 and 2.213) indicated independence of residuals. We applied partial correlation to analyze the correlation between our variables.

A glance at Table 2 makes the picture obvious. After controlling for age and gender, ACBL shows a weak positive correlation with every airway parameter we measured. The strongest association was with CSA min ($r = 0.334$, $P < 0.001$), followed closely by retropalatal volume ($r = 0.225$, $P = 0.002$), total airway volume ($r = 0.202$, $P = 0.006$), and retroglossal volume ($r = 0.144$, $P = 0.047$). Put simply, a longer Sella–Nasion measurement with more spacious airways and, what matters most clinically, a wider narrowest cross-section.

ACBI painted a completely different picture. It did not demonstrate any statistically significant association with any of the airway measurements. After controlling for age and gender, the partial correlation coefficients ranged from 0.011 to 0.038, indicating only negligible positive correlations. Bottom line: whether the anterior cranial base tilts steeply or sits relatively flat made no measurable difference to any airway variable we examined in this cohort.

Discussion

Anterior cranial base length showed a positive correlation with the total airway volume in this observational study. This was also observed for each compartment individually. Cranial base inclination, on the other hand, showed no meaningful relationship with any of the airway parameters we tested.

Multiple regression analysis further confirmed that ACBL, together with age and sex, independently predicted total airway volume and CSA min. These findings are consistent with those of Habumugisha J et al., who demonstrated, using multiple linear regression, that anterior cranial base length was a significant predictor of pharyngeal airway volume.[9]

Cranial base length has a specific role in the proper functioning of the airway mechanism. It serves as a stable structural foundation for the maxilla and influences the spatial relationship of the facial skeleton during growth.[8] A longer S-N distance implies a more anteriorly positioned Nasion relative to Sella, which effectively expands the anteroposterior dimension of the skeletal framework housing the upper airway.[3,9] Nath and colleagues reported something very similar when they compared airway volumes across skeletal classes and found that variations in the cranial base region were closely tied to the differences they observed.[3]

The correlation with CSA min (r = 0. 0.334) deserves particular attention from a clinical standpoint. CSA min is not merely an anatomical curiosity; it is the functional bottleneck of the airway. It determines airflow resistance more than any other single measurement, and a critically narrow CSA min has been shown to predict pharyngeal wall collapse during sleep.[17] If ACBL can flag patients who are likely to have a tighter bottleneck, it becomes a useful screening adjunct — especially because it is measurable on any CBCT that captures the skull base, even if the airway itself was not the original reason for the scan.[16]

Males in our sample had both longer cranial bases and larger airways than females, which is consistent with what El and Palomo documented using CBCT in a North American population.[18] The airway volume gap was roughly 2,768 mm^3 — not a trivial difference. Part of this is undoubtedly attributable to general skeletal size dimorphism, but hormonal factors and differences in soft tissue proportions likely play a role as well.[19]

Clinicians should not overlook this gap between the sexes. Between the ages of roughly eight and fifteen, the craniofacial skeleton and pharyngeal soft tissues of boys and girls follow quite different growth curves. Testosterone-driven periosteal apposition tends to enlarge the bony pharyngeal envelope in males, while estrogen promotes earlier skeletal maturation but smaller overall dimensions in females.[19] These hormonal influences may partly explain why, despite similar chronological ages, the two sexes presented with noticeably different airway volumes in our sample. From a clinical standpoint, this suggests that sex-specific normative values for airway dimensions would be more meaningful than pooled reference ranges when screening growing patients for potential airway insufficiency.

Now, about the inclination. We did not find a significant association between ACBI and any airway measurement, which may seem surprising given that some authors have hypothesized a role for cranial base angulation in determining nasopharyngeal depth.[4] There is a logic to our negative finding: the anterior cranial base angle, once established early in childhood, changes very little after the age of eight.[8] The airway, by contrast, is a dynamic structure whose dimensions are governed primarily by soft tissue variables — tongue volume, soft palate length, lymphoid tissue, and body weight — all of which continue to change throughout adolescence. An angular parameter that is essentially fixed may simply lack the explanatory power to account for variation in a structure that is anything but fixed. Kochhar AS et al. observed that airway volume varied across skeletal patterns, with smaller airway dimensions commonly seen in Class II subjects.[10] Class II subjects have smaller airways overall, which is consistent with the existing body of evidence.[5,20] The retrognathic mandible typical of Class II pushes the tongue base posteriorly and encroaches on the retroglossal space. Add to that a potentially shorter cranial base, as has been reported in some Class II populations, and you have a double disadvantage. However, an anterior mandible that opens the retroglossal region helps Class III patients. Our data, while not designed to compare classes statistically, were broadly consistent with this narrative. These observations carry practical weight for orthodontic treatment planning. When a patient presents with a Class II skeletal relationship and a short anterior cranial base, the likelihood of a constricted pharyngeal airway is elevated on two counts: the mandible is positioned posteriorly, and the overall anteroposterior skeletal scaffold is reduced.[5,13] In such individuals, treatment strategies that advance the mandible, whether through functional appliances in growing patients or surgical mandibular advancement in adults, may confer airway benefits in addition to improving facial aesthetics and occlusion. Conversely, treatment plans involving premolar extractions and significant retraction of the anterior dentition should be carefully evaluated in patients with borderline airway dimensions, as further posterior displacement of the tongue base could worsen a compromised retroglossal space.[6] Habumugisha and colleagues have recently proposed prediction models that combine cranial base measurements with midsagittal airway cross-sections to estimate total pharyngeal volume, reinforcing the idea that cranial base morphology should not be overlooked in comprehensive airway assessment.[9]

It is worth underscoring what CBCT brought to this investigation that older imaging could not. A lateral cephalogram superimposes all bilateral structures and gives no volumetric information whatsoever.[11] We were able to separately quantify the retropalatal and retroglossal compartments, identify the CSA min at its precise anatomical level, and correlate all of this with cranial base parameters measured in three dimensions rather than projected onto a flat film.[12] None of this would have been possible with conventional radiography.

A recent systematic review with network meta-analysis concluded that patients with different craniofacial patterns do indeed exhibit measurably different upper airway volumes, though the magnitude of these differences varies across populations and measurement protocols.[13] Our findings align with that conclusion and extend it by demonstrating that among the craniofacial variables studied, it is the linear dimension of the anterior cranial base rather than its angular orientation that carries the stronger association with airway size. From a chairside perspective, this matters: it points clinicians to a single concrete, readily available number rather than a vague, skeletal classification. Furthermore, emerging work on artificial intelligence-assisted airway analysis of CBCT datasets suggests that integrating skeletal parameters, such as ACBL, into automated screening algorithms could improve early detection of patients at risk for obstructive breathing disorders.[11] As these technologies mature, incorporating cranial base data into machine-learning models may provide a more personalized and accurate airway risk profile than relying on airway measurements alone.

We would be remiss not to acknowledge several shortcomings. A cross-sectional study always establishes association rather than causation. We do not know, and cannot claim from these data, that a short cranial base causes a small airway. Other variables we did not measure — body mass index, soft palate thickness, adenoid size, tonsil grade, tongue volume — could confound the relationship. Our sample came from a single center in Taxila, and whether these findings generalize to other Pakistani populations, let alone other ethnic groups, remains to be established. Future work should ideally be longitudinal, tracking cranial base growth alongside airway changes in the same individuals over time, and should incorporate the confounders we were unable to control for here. Moreover, all CBCT scans in this study were obtained in an upright seated position, whereas the pharyngeal airway behaves differently in the supine posture adopted during sleep. In practice, this means that our static measurements, taken with the patient sitting upright and awake, do not necessarily reflect how the same airway behaves when the patient is asleep and the pharyngeal muscles lose tone. Pairing future anatomical studies with overnight polysomnography would go a long way toward connecting structure with function. We should also note that lumping eight-year-olds together with eighteen-year-olds glosses over substantial developmental variation; breaking the cohort into tighter age bands in subsequent work might uncover trends that our pooled analysis was not powered to detect.

Conclusion

A longer anterior cranial base is associated with both a larger pharyngeal airway volume and a wider minimum cross-sectional area. The angular tilt of the cranial base, by contrast, does not appear to influence airway dimensions in any clinically meaningful way. From a clinical perspective, the findings may be relevant for orthodontists and oral surgeons. Since ACBL can be measured directly from standard CBCT images, it could be considered as part of routine airway evaluation. Including this parameter may assist clinicians when assessing airway characteristics in growing patients, especially those with malocclusion or possible breathing-related concerns.

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Author Contributions

SF: Conception, design of the work, and approval for final submission

WUK: Validation of data, interpretation, write-up of results, and approval for final submission

MH: Revising, editing, supervising for intellectual content, and approving for final submission

ST: Writing the original draft, proofreading, and approval for final submission

SI: Data acquisition, curation, statistical analysis, and approval for final submission

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SF is the nominated guarantor and takes full responsibility for the overall content and integrity of the work