E-ISSN 2250-0944
ISSN 2250-1150
doi: 10.31838/ijprt/16.02.570

Research Article

Longitudinal Assessment of Cervical Vertebral Morphometric Changes and Their Relationship with Mandibular Growth in Pakistani Orthodontic Patients: Implications for Orthodontic and Implant Treatment Planning

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Received: 11.07.2026, Revised: 27.08.2026, Accepted: 08.09.2026

ABSTRACT

Background: Cervical vertebral morphology changes during skeletal maturation and may provide clinically useful information for assessing craniofacial growth.

Objective: To evaluate longitudinal changes in the anterior height, posterior height, and anteroposterior length of C3 and C4 cervical vertebrae and to determine their relationship with mandibular length increment in Pakistani orthodontic patients, with consideration of their potential implications for orthodontic and implant treatment planning.

Materials and Methods: This longitudinal observational study included 60 Pakistani orthodontic patients. Baseline and approximately 24-month follow-up lateral cephalograms were evaluated. Mandibular length was assessed using Ar–Pog, and mandibular length increment (MLI) was calculated as follow-up Ar–Pog minus baseline Ar–Pog. Paired t-tests assessed longitudinal changes, while Pearson correlation coefficients evaluated relationships between changes in cervical vertebral dimensions and MLI.

Results: The mean baseline age was 12.4 ± 2.6 years. Mandibular length increased from 75.80 ± 9.10 mm at baseline to 83.00 ± 10.02 mm at follow-up, corresponding to a mean MLI of 7.20 mm ($p < 0.001$). All six cervical vertebral dimensions increased significantly over the observation period (all $p < 0.001$). The strongest association was observed between ΔAP4 and MLI ($r = 0.39$, $p = 0.002$).

Conclusion: C3 and C4 cervical vertebral dimensions increased concurrently with mandibular length over approximately two years. The modest positive associations between cervical vertebral dimensional changes and mandibular length increment suggest that quantitative cervical vertebral morphometry may provide supplementary information when evaluating skeletal development.

Keywords: Cervical Vertebral Maturation, Mandibular Growth, Cephalometry, Skeletal Maturity, Orthodontics, Implant Treatment Planning.

INTRODUCTION

Accurate assessment of craniofacial growth and skeletal maturity is fundamental to orthodontic diagnosis and treatment planning. The timing of growth modification, particularly in patients with skeletal discrepancies, depends not only on chronological age but also on individual biological maturation. Mandibular growth is particularly important because changes in mandibular length and position can substantially influence facial proportions, sagittal relationships, and the timing and effectiveness of dentofacial orthopedic interventions. Consequently, reliable indicators of skeletal maturation that can be incorporated into routine orthodontic records are clinically valuable (1,2).

Cervical vertebral maturation (CVM) assessment has emerged as a practical method for evaluating skeletal maturity from lateral cephalograms routinely obtained for orthodontic diagnosis. The method evaluates developmental changes in the cervical vertebrae, particularly C2, C3, and C4, including alterations in vertebral body shape and concavity of the inferior borders (3). The modified CVM method proposed by Baccetti et al. describes six maturational stages and was developed to assist in identifying the timing of the pubertal growth spurt and optimizing the timing of dentofacial orthopedic treatment (4). Because the cervical vertebrae are visible on standard lateral cephalograms, CVM assessment avoids the need for an additional radiographic examination solely for skeletal maturation assessment (3,4).

Several longitudinal investigations have demonstrated an association between cervical vertebral maturation and mandibular growth. O'Reilly and Yanniello reported significant changes in mandibular length and other mandibular dimensions in relation to cervical vertebral maturation stages (5). Similarly, longitudinal data from the Burlington Growth Center demonstrated an association between cervical maturation stages and mandibular growth, with important changes occurring during the circumpubertal period (6). More recent investigations have also examined quantitative cervical vertebral characteristics in relation to craniofacial growth, suggesting that measurable vertebral dimensions may provide complementary information beyond categorical maturation staging (7). However, much of the existing literature has focused on maturation stages rather than longitudinal changes in specific vertebral dimensions. Furthermore, skeletal maturation and craniofacial growth patterns may vary across populations, emphasizing the importance of population-specific evidence.

Quantitative assessment of cervical vertebral dimensions may therefore provide a complementary approach to conventional maturation staging. Measurements of vertebral anterior height, posterior height, and anteroposterior length can characterize structural changes occurring during growth and can be examined directly in relation to concurrent changes in mandibular length. Such quantitative measurements may be particularly useful for describing growth-related changes while avoiding the assumption that cervical vertebral morphology alone can accurately predict individual mandibular growth. Systematic reviews have highlighted methodological variability and limitations in the evidence supporting CVM as an indicator of pubertal growth, emphasizing the need for longitudinal investigations and cautious interpretation of its clinical utility (8).

Assessment of skeletal growth also has relevance to restorative and implant treatment planning. Dental implants are osseointegrated structures and do not follow the continued eruption and positional changes of natural teeth during craniofacial growth. Consequently, implant placement in patients with substantial residual skeletal growth may result in positional discrepancies and other complications (9,10). Evidence from systematic reviews indicates that implant treatment in growing patients requires careful consideration of skeletal and dentoalveolar growth and is generally approached cautiously until growth is substantially completed (11). Although cervical vertebral dimensions cannot independently determine the appropriate timing of implant placement, information regarding skeletal development may provide supplementary context when growth-dependent orthodontic and implant treatment decisions are considered.

Despite the established relationship between cervical vertebral maturation and mandibular growth, limited longitudinal evidence has examined quantitative changes in individual C3 and C4 vertebral dimensions alongside mandibular length in Pakistani orthodontic patients. Therefore, the present study was undertaken to evaluate longitudinal changes in the anterior height, posterior height, and anteroposterior length of C3 and C4 and to determine their relationship with mandibular length increment over approximately two years. The study also examined whether the direction and magnitude of these associations were observed in both male and female patients. By evaluating quantitative cervical vertebral changes alongside mandibular growth, this study aimed to provide population-specific evidence regarding the potential supplementary role of cervical vertebral morphometry in assessing skeletal development and informing growth-dependent orthodontic and implant treatment considerations.

METHODOLOGY

This longitudinal observational study was conducted among orthodontic patients receiving care at Department of orthodontics, Altamash Institute of Dental Medicine, Karachi, Pakistan. The study included 60 patients between 8 and 18 years of age, comprising 30 males and 30 females. Patients were selected from the orthodontic patient population according to predefined eligibility criteria and were followed longitudinally for approximately 24 months. The study was designed to evaluate growth-related changes in the morphology of the third and fourth cervical vertebrae (C3 and C4) and to determine whether these changes were associated with concurrent changes in mandibular length. The study protocol was reviewed and approved by the Altamash Institute of Dental Medicine, Ethical Review Committee. All procedures were conducted in accordance with applicable ethical principles for research involving human participants. Written informed consent was obtained from the parents or legal guardians of participants younger than 18 years, and assent was obtained from participants where applicable.

Patients aged 8–18 years who had suitable baseline and follow-up lateral cephalometric radiographs separated by approximately 24 months were eligible for inclusion. Both male and female orthodontic patients were included to permit assessment of longitudinal changes and sex-specific associations. Radiographs were considered eligible when the cervical vertebrae and relevant craniofacial landmarks were clearly visible and of sufficient diagnostic quality to permit reliable identification and measurement. Patients were excluded when either the baseline or follow-up radiograph was of inadequate quality, when the cervical vertebral region was obscured or distorted, when relevant anatomical landmarks could not be identified reliably, or when conditions or previous interventions were present that could substantially alter normal craniofacial growth or cervical vertebral morphology. Patients without a suitable longitudinal radiographic record or with incomplete measurements at either assessment point were also excluded from the final analysis. The final sample therefore consisted of 60 patients with paired baseline and follow-up lateral cephalograms.

Lateral cephalometric radiographs obtained at baseline and at approximately 24 months were used for the longitudinal assessment. Radiographs were evaluated using a standardized cephalometric measurement protocol. The cervical vertebrae were assessed on the lateral cephalograms, with particular attention to C3 and C4, which were selected because of their established relevance to cervical vertebral maturation and their visibility on routine orthodontic cephalograms. Three linear dimensions were assessed for each vertebra: anterior vertebral body height, posterior vertebral body height, and anteroposterior vertebral body length. Accordingly, six cervical vertebral measurements were obtained for each radiographic assessment: C3 anterior height (AH3), C3 posterior height (PH3), C3 anteroposterior length (AP3), C4 anterior height (AH4), C4 posterior height (PH4), and C4 anteroposterior length (AP4). All measurements were recorded in millimetres. The same anatomical definitions and measurement procedures were applied to baseline and follow-up radiographs to minimize methodological variation between assessment periods.

Mandibular length was assessed on the same lateral cephalograms using the Ar–Pog measurement. For longitudinal analysis, mandibular length increment (MLI) was defined as the difference between mandibular length at follow-up and mandibular length at baseline. Thus, MLI represented the amount of mandibular length growth occurring during the approximately 24-month observation period. Similarly, longitudinal changes in each cervical vertebral dimension were calculated by subtracting the baseline measurement from the corresponding follow-up measurement (Δ measurement = follow-up measurement − baseline measurement). Positive values therefore represented an increase in the respective cervical vertebral dimensions over the observation period. This approach permitted direct comparison of individual changes in AH3, PH3, AP3, AH4, PH4, and AP4 with the amount of mandibular length growth occurring during the same period.

All cephalometric measurements were performed by a trained examiner experienced in cephalometric analysis. To improve measurement consistency, the same examiner used the same anatomical landmarks and measurement protocol for all radiographs. Where possible, radiographs were assessed in a standardized sequence without access to previously recorded measurements. To evaluate intra-examiner reliability, a randomly selected subset of radiographs was remeasured after an interval of approximately two weeks, and measurement agreement was assessed using [intraclass correlation coefficient/appropriate reliability statistic]. Any discrepancies were reviewed according to the predefined landmark identification protocol. If an inter-examiner reliability assessment was performed, this should be reported using the actual method and reliability statistics. These procedures were used to minimize random and systematic measurement error in the longitudinal assessment.

Data were entered into SPSS version 30. Continuous variables were summarized using means and standard deviations, while categorical variables were summarized using frequencies and percentages. Baseline and follow-up measurements of mandibular length and each of the six cervical vertebral dimensions were compared using paired t-tests because measurements were obtained from the same individuals at the two time points. Mean changes and corresponding statistical significance were determined for AH3, PH3, AP3, AH4, PH4, and AP4. Pearson correlation coefficients were calculated to determine the strength and direction of the relationships between longitudinal changes in each cervical vertebral dimension and mandibular length increment. Correlations were assessed separately for ΔAH3, ΔPH3, ΔAP3, ΔAH4, ΔPH4, and ΔAP4. Correlation analyses were also examined according to sex to determine whether the observed positive relationships were present among both male and female participants. Statistical tests were two-tailed, and a p-value of <0.05 was considered statistically significant.

The longitudinal analytical approach was selected to distinguish individual growth-related changes from differences between unrelated age groups. By comparing each participant with their own baseline measurements, the study assessed concurrent changes in cervical vertebral morphology and mandibular length over approximately two years. The primary outcome measures were the longitudinal changes in the six C3 and C4 vertebral dimensions, while the principal growth-related outcome was mandibular length increment. The analysis was intended to determine whether quantitative cervical vertebral changes were associated with mandibular growth rather than to establish cervical vertebral dimensions as independent predictors of mandibular growth or definitive indicators of treatment timing. Accordingly, the findings were interpreted as evidence of the potential supplementary value of cervical vertebral morphometry in assessing skeletal development, with cautious consideration of its possible relevance to growth-dependent orthodontic and implant treatment planning.

RESULTS

A total of 60 Pakistani orthodontic patients were included in the longitudinal analysis, comprising 30 males (50.0%) and 30 females (50.0%). The mean baseline age of the participants was 12.4 ± 2.6 years. All participants had paired baseline and follow-up lateral cephalometric radiographs separated by approximately 24 months and fulfilled the predefined eligibility criteria. The demographic characteristics of the study population are presented in Table 1.

Table 1. Demographic Characteristics of the Study Population

Characteristic	n	%
Total participants	**60**	**100.0**
Sex		
Male	30	50.0
Female	30	50.0
Mean baseline age (years)	**12.4 ± 2.6**	—
Follow-up duration (months)	**Approximately 24**	—

Longitudinal comparison demonstrated significant increases in all six assessed cervical vertebral dimensions between baseline and follow-up. C3 anterior height (AH3) increased from 7.60 ± 1.52 mm to 10.68 ± 2.04 mm, representing a mean increase of 3.08 mm. C3 posterior height (PH3) increased by 2.32 mm, while C3 anteroposterior length (AP3) increased by 1.46 mm. Similarly, C4 anterior height (AH4) increased by 2.78 mm, C4 posterior height (PH4) by 1.73 mm, and C4 anteroposterior length (AP4) by 1.67 mm. All six longitudinal changes were statistically significant (all $p < 0.001$), demonstrating significant growth-related increases in the measured dimensions of both C3 and C4. The findings are summarized in Table 2

Table 2. Longitudinal Changes in C3 and C4 Cervical Vertebral Dimensions

Cervical vertebral parameter	Baseline, Mean ± SD (mm)	Follow-up, Mean ± SD (mm)	Mean change (mm)	p-value
C3 anterior height (AH3)	7.60 ± 1.52	10.68 ± 2.04	3.08	<0.001
C3 posterior height (PH3)	9.04 ± 1.61	11.36 ± 1.89	2.32	<0.001
C3 anteroposterior length (AP3)	7.86 ± 1.37	9.32 ± 1.68	1.46	<0.001
C4 anterior height (AH4)	6.72 ± 1.78	9.50 ± 2.05	2.78	<0.001
C4 posterior height (PH4)	9.18 ± 1.77	10.91 ± 1.96	1.73	<0.001
C4 anteroposterior length (AP4)	7.76 ± 1.45	9.43 ± 1.53	1.67	<0.001

Paired t-test; $p < 0.05$ was considered statistically significant.

Mandibular length also demonstrated a significant longitudinal increase during the approximately 24-month follow-up period. Mean Ar–Pog increased from 75.80 ± 9.10 mm at baseline to 83.00 ± 10.02 mm at follow-up, corresponding to a mean mandibular length increment (MLI) of 7.20 mm. This longitudinal increase was statistically significant ($p < 0.001$), indicating significant mandibular growth during the observation period. The mandibular growth findings are presented in Table 3.

Table 3. Longitudinal Change in Mandibular Length

Mandibular parameter	Baseline, Mean ± SD (mm)	Follow-up, Mean ± SD (mm)	Mean MLI (mm)	p-value
Ar–Pog	75.80 ± 9.10	83.00 ± 10.02	7.20	<0.001

MLI = mandibular length increment; MLI was calculated as follow-up Ar–Pog minus baseline Ar–Pog. Paired t-test; $p < 0.05$ was considered statistically significant. Pearson correlation analysis demonstrated positive associations between longitudinal changes in all six cervical vertebral dimensions and mandibular length increment. Correlation coefficients ranged from 0.28 to 0.39, indicating modest positive relationships. The strongest association was observed between the change in C4 anteroposterior length (ΔAP4) and MLI ($r = 0.39$, $p = 0.002$). Changes in C3 anterior height, C3 posterior height, C3 anteroposterior length, C4 anterior height, and C4 posterior height were also positively correlated with MLI, with correlation coefficients ranging from 0.28 to 0.35. Thus, participants with greater longitudinal increases in cervical vertebral dimensions tended to demonstrate greater mandibular length increments. The correlation analysis is presented in Table 4.

Table 4. Correlation between Cervical Vertebral Morphometric Changes and Mandibular Length Increment

Cervical vertebral change	Pearson r with MLI	p-value
ΔAH3	0.31	0.016
ΔPH3	0.28	0.030

ΔAP3	0.34	0.008
ΔAH4	0.35	0.006
ΔPH4	0.30	0.020
ΔAP4	**0.39**	**0.002**

MLI = mandibular length increment; Δ = follow-up measurement − baseline measurement. Pearson correlation coefficient; $p < 0.05$ was considered statistically significant.

Sex-stratified analysis demonstrated positive correlations between cervical vertebral dimensional changes and MLI in both males and females. Among males, correlation coefficients ranged from 0.30 to 0.41, with statistically significant associations observed for ΔAH4 ($r = 0.37$, $p = 0.043$) and ΔAP4 ($r = 0.41$, $p = 0.025$). Among females, correlation coefficients ranged from 0.27 to 0.37, with a statistically significant association observed between ΔAP4 and MLI ($r = 0.37$, $p = 0.043$). Although not all sex-specific correlations reached statistical significance, all observed correlations were positive, indicating a consistent direction of association in both groups. The sex-stratified correlations are presented in Table 5.

Table 5. Sex-stratified Correlations between Cervical Vertebral Morphometric Changes and Mandibular Length Increment

Cervical vertebral change	Male r	Male p-value	Female r	Female p-value
ΔAH3	0.32	0.083	0.29	0.120
ΔPH3	0.30	0.106	0.27	0.148
ΔAP3	0.35	0.058	0.33	0.074
ΔAH4	0.37	0.043	0.34	0.064
ΔPH4	0.31	0.095	0.28	0.133
ΔAP4	0.41	0.025	0.37	0.043

MLI = mandibular length increment; Δ = follow-up measurement − baseline measurement. Pearson correlation analysis; $p < 0.05$ was considered statistically significant.

DISCUSSION

The present longitudinal study evaluated changes in the quantitative morphology of the C3 and C4 cervical vertebrae and examined their relationship with mandibular length increment. The principal findings were that all six assessed cervical vertebral dimensions AH3, PH3, AP3, AH4, PH4, and AP4—increased significantly during the observation period, accompanied by a significant increase in mandibular length. Furthermore, changes in all six cervical vertebral dimensions demonstrated positive associations with mandibular length increment, although the magnitude of these correlations was modest. The strongest overall association was observed between the change in C4 anteroposterior length (ΔAP4) and mandibular length increment ($r = 0.39$, $p = 0.002$). Positive associations were also observed in both males and females, although not all sex-specific correlations reached statistical significance (12).

The significant longitudinal increases observed in all six cervical vertebral measurements are consistent with the concept that cervical vertebral morphology undergoes measurable structural changes during skeletal maturation (13). Conventional cervical vertebral maturation (CVM) assessment is primarily based on qualitative changes in vertebral body shape and inferior border concavity, particularly involving C2, C3, and C4. The improved CVM method described by Baccetti et al. established maturational stages based on these morphological characteristics and was developed to improve assessment of skeletal maturity and the timing of mandibular growth (4). A subsequent modification further refined the CVM approach by emphasizing progressive changes in the morphology of C2, C3, and C4 and their relationship with mandibular growth (2). The present findings complement this qualitative framework by demonstrating that individual linear dimensions of C3 and C4 also increase significantly over time.

The observed mandibular growth is also consistent with previous longitudinal research linking cervical vertebral maturation with mandibular development. O'Reilly and Yanniello demonstrated that changes in mandibular length, corpus length, and ramus height were associated with specific stages of cervical vertebral maturation in a longitudinal sample of adolescent females (5). Similarly, Franchi et al.

reported significant increases in total mandibular length during the interval between cervical vertebral maturation stages associated with the pubertal growth period, supporting an association between cervical maturation and mandibular growth (14). These observations support the biological plausibility of the present findings because both cervical vertebral development and mandibular growth represent components of the broader skeletal maturation process (15). The positive correlations observed between changes in cervical vertebral dimensions and mandibular length increment provide further support for an association between cervical vertebral development and mandibular growth. Correlation coefficients in the overall sample ranged from 0.28 to 0.39, indicating modest but consistently positive relationships. The strongest relationship was observed for ΔAP4 ($r = 0.39$), followed by ΔAH4 ($r = 0.35$), ΔAP3 ($r = 0.34$), ΔAH3 ($r = 0.31$), ΔPH4 ($r = 0.30$), and ΔPH3 ($r = 0.28$).

Positive correlations were observed for all six cervical vertebral changes in both males and females, indicating that the direction of the relationship was generally consistent across sex groups (16). Among males, the strongest association was observed for ΔAP4 ($r = 0.41$, $p = 0.025$), followed by ΔAH4 ($r = 0.37$, $p = 0.043$). Among females, ΔAP4 again demonstrated the strongest association ($r = 0.37$, $p = 0.043$). The remaining sex-specific correlations did not consistently reach statistical significance, which may partly reflect the smaller number of participants within each subgroup. Importantly, the present analysis did not formally test sex-by-cervical-dimension interaction effects; therefore, it cannot establish that sex significantly modifies the relationship between cervical vertebral changes and mandibular growth. Instead, the findings indicate that positive associations were present in both groups, with the relationship involving ΔAP4 being particularly consistent.

The findings should also be interpreted considering the broader debate concerning the reliability and clinical usefulness of CVM-based assessment. Although CVM assessment is widely used because cervical vertebrae can be evaluated on routine lateral cephalograms without requiring an additional radiographic examination, systematic reviews have identified methodological heterogeneity and limitations in the evidence supporting CVM as a precise indicator of pubertal growth (6). More recent evidence has similarly suggested that CVM should preferably be interpreted alongside other skeletal maturity indicators rather than used in isolation (17). These observations are relevant to the interpretation of the present study. Quantitative measurements may provide additional objective information about structural change, but the present findings do not establish that quantitative C3 or C4 dimensions can accurately identify the timing of an individual's peak mandibular growth (18).

An important strength of the present investigation is its longitudinal design. Rather than comparing unrelated individuals from different age groups, each participant served as their own reference through comparison of baseline and follow-up radiographs. This approach reduces some of the confounding associated with cross-sectional age comparisons and allows direct assessment of growth-related change. The study also has several limitations that should be considered when interpreting the findings. First, the sample size was relatively small, particularly for the sex-stratified analyses, which may have limited statistical power and contributed to the lack of significance for some correlations. Second, the study was conducted among Pakistani orthodontic patients, and the findings may not be directly generalizable to other ethnic or clinical populations.

Therefore, a particular measurement or amount of dimensional change should not be interpreted as indicating a specific stage of skeletal maturity. The findings have potential relevance to orthodontic treatment planning, particularly in clinical situations in which the timing of growth modification is important. Previous longitudinal studies have demonstrated that cervical vertebral maturation is associated with periods of accelerated mandibular growth (4). The significant concurrent increase in mandibular length and cervical vertebral dimensions observed in the present study suggests that quantitative cervical vertebral assessment may provide additional information about ongoing skeletal development when interpreted alongside chronological age, clinical examination, dental development, and other skeletal maturity indicators (19).

The potential implications for implant treatment planning should likewise be interpreted cautiously. Dental implants behave differently from natural teeth during continued craniofacial growth and may become relatively infraoccluded or displaced as surrounding dentoalveolar structures continue to develop. A systematic review of dental implants in growing patients reported complications and positional changes associated with implant placement during ongoing growth and emphasized that treatment in growing individuals requires careful case selection and follow-up (20). More recent systematic-review evidence has similarly indicated that implant treatment in growing patients depends on factors including the stage of jaw growth, anatomical characteristics, and the clinical circumstances of the missing teeth, while conservative management until growth completion remains common (21). In this context, the present findings may provide supplementary information about skeletal development, but they do not establish cervical vertebral morphometry as a method for determining the appropriate timing of implant placement. Implant decisions should continue to incorporate comprehensive clinical, radiographic, dental, skeletal, and prosthodontic considerations.

The present study therefore contributes population-specific longitudinal evidence showing that C3 and C4 cervical vertebral dimensions undergo measurable increases concurrently with mandibular growth in Pakistani orthodontic patients. The consistent positive correlations observed across all six measurements, particularly the relationship between ΔAP4 and mandibular length increment, support the possibility that quantitative cervical vertebral morphometry may complement existing approaches to skeletal growth assessment. At the same time, the modest correlation strengths and limitations of the study design emphasize that these measurements should not be interpreted as precise predictors of individual mandibular growth or as definitive indicators of treatment timing.

Future investigations should include larger, multicenter Pakistani samples with longer follow-up periods and multiple radiographic assessments across the entire growth interval. Incorporating conventional CVM staging, quantitative vertebral measurements, mandibular growth velocity, skeletal age, and other established indicators of skeletal maturation within the same longitudinal cohort would permit more comprehensive comparisons. Multivariable models could also determine whether specific cervical vertebral dimensions provide independent information after accounting for chronological age, sex, baseline mandibular length, and other relevant growth-related variables. Such research may ultimately clarify whether quantitative C3 and C4 morphometry can be translated into clinically useful tools for individualized orthodontic treatment planning and more informed assessment of growth-dependent implant considerations.

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