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Association Between Cervical Vertebral Maturation and Dental Calcification Stages in Children and Adolescents Aged 7-17 Years: A Retrospective Cross-Sectional Study

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Abstract

Introduction

The timing of orthopedic and orthodontic treatment in the pubertal growth spurt necessitates an accurate prediction of skeletal maturity. Cervical vertebral maturation (CVM) staging on lateral cephalograms is widely used, whereas dental calcification can be read from routine panoramic radiographs. This study aimed to evaluate the association between cervical vertebral maturation stages and dental calcification stages of selected mandibular teeth in children and adolescents aged 7-17 years. A secondary objective was to assess whether these associations differed by sex.

Materials and Methods

This retrospective cross-sectional study included 300 children and adolescents aged 7-17 years selected using quota-based sampling, with 25 males and 25 females represented in each of the six cervical vertebral maturation stages (CS1-CS6). Lateral cephalograms were taken by the Baccetti method to be used for staging CVM. Panoramic radiographs were taken to assess the calcification status of the left mandibular canine (33), first premolar (34), second premolar (35), and second molar (37) according to Demirjian's score (A-H). The Spearman rank correlation, Fisher r-to-z test, Kruskal-Wallis test, and Mann-Whitney U test were used. Quadratic weighted kappa was used to measure intra-examiner reliability.

Results

There were significant positive correlations between all four teeth and CVM stage ($p < 0.001$). Spearman's ρ for the second premolar, canine, first premolar, and second molar was 0.758, 0.756, 0.683, and 0.628, respectively, in the total sample. The second premolar showed the strongest correlation in boys ($\rho = 0.807$), whereas the canine showed the strongest correlation in girls ($\rho = 0.763$). No significant sex differences were observed in the correlation coefficients ($p > 0.05$). Chronological age showed a stronger correlation with CVM stage ($\rho = 0.897$) than any individual tooth. At the pubertal growth peak (CS3-CS4), the mandibular canine was most frequently at stage E in boys (21/50, 42%) and stage F in girls (22/50, 44%). Intra-examiner agreement was high, with weighted κ values ranging from 0.949 to 0.979. Intra-examiner reliability was high, with weighted kappa values ranging from 0.949 to 0.979 across the assessed variables.

Conclusions

There is a high correlation between calcification stages of the mandibular canine and second premolar and those of cervical vertebral maturation, and it can be used as an additional radiological, non-radiation screening tool of skeletal maturity in panoramic radiographs. They should not be used as a substitute for skeletal indicators where exact timing of the treatment is important. These cross-sectional associations do not establish temporal prediction, diagnostic accuracy, or the optimal timing of orthodontic treatment.

Categories: Dentistry
Keywords: cervical vertebral maturation, demirjian method, dental calcification, lateral cephalogram, orthodontic treatment timing, panoramic radiograph, pubertal growth spurt, skeletal maturity

Introduction

The timing of the beginning of the treatment of malocclusions, both functional and orthopedic, is of great importance to the success of that treatment. Growth modification is most effective when it occurs during the pubertal growth spurt; thus, a reliable method for determining where a child is on the growth curve is needed [1]. It is not a good indicator, as the age of puberty can differ significantly from one child to another and from one sex to the other. Therefore, skeletal maturity indicators have been developed, and the hand-wrist radiograph was the reference standard [2].

An extra radiograph is needed for the hand-wrist method. Cervical vertebrae are, on the other hand, visible on a lateral cephalogram that is routinely obtained for orthodontic diagnosis. The change in the second to fourth cervical vertebrae correlates well with mandibular growth and body height [3]. Hassel and Farman applied these modifications to a cervical vertebral maturation index (CVM) [4], which, later, was further divided into six stages (CS1-CS6) by Baccetti et al., with the pubertal peak occurring between CS3 and CS4 [5]. The method is now common, but it has been suggested that it is not reproducible if not calibrated [6].

Another perspective of biological maturity is dental development. The development of teeth is progressive and predictable and relatively independent of nutritional and endocrine variation as compared to skeletal development [7]. Demirjian et al. have suggested eight calcification stages that were based on shape rather than length, and therefore are reproducible on panoramic radiographs [8]. Given that panoramic radiographs are obtained more frequently than cephalograms in routine dental practice, an established correlation between dental and skeletal maturation would enable dentists to screen patients for the growth spurt and make appropriate referrals [9].

Mineralization of the mandibular canine is reported to start at the same time as the pubertal growth spurt [8], and this was confirmed by Coutinho et al. [10] for the canine. Subsequent research revealed that moderate to strong correlations existed between dental calcification and skeletal maturity, but the tooth to which this was most closely related differed from population to population, sex to sex [11]. The mandibular second molar has been suggested as a potentially useful indicator due to its presence on most films [12], and the canine has been most associated with the growth spurt. Researchers have shown that dental maturity is not predictive, but rather a good rule-out [13].

These relationships should be determined in each population because there are differences in dental and skeletal maturation. In this study, the statistical relationship between the cervical vertebral maturation stages and Demirjian calcification stages of the mandibular canine, first premolar, second premolar, and second molar has been evaluated and compared between boys and girls in children. The null hypothesis was that there would be no correlation between the dental calcification stage and the CVM stage.

Materials And Methods

Study design: a cross-sectional, retrospective, radiographical study

Setting

This retrospective cross-sectional study used patient records from the Department of Pediatric and Preventive Dentistry, Vyas Dental College and Hospital, Jodhpur, in collaboration with Pacific Dental College and Hospital, Udaipur, and Awadh Dental College and Hospital, Jamshedpur. Records of eligible patients examined between July and December 2024 were assessed for inclusion. This study has been approved by the Institutional Ethics Committee. Parents/Guardians were asked for consent to use the radiographs for research at the time of treatment, and patient identifiers were removed before being analyzed. The study followed the Declaration of Helsinki. The study received ethical approval from the Ethics Committee of Vyas Dental College and Hospital, Jodhpur, Rajasthan, India (Approval No. VDCH/IEC/2024/10).

Written informed consent was obtained from the parents or legal guardians of participants younger than 18 years. Age-appropriate assent was also obtained from participating children and adolescents in accordance with the approved ethical protocol.

Sample Size

The sample size was calculated for a correlation design with Fisher's z transformation:

$$
n=\left(\frac{Z_{\alpha/2}+Z_{\beta}}{C}\right)^2+3
$$

$$
C=\frac{1}{2}\ln\left(\frac{1+r}{1-r}\right)
$$

With two-tailed α=0.05, power=90%, and an expected value of r=0.40, the minimum number required was 62/sex (124 in total); this was raised to 138/sex by assuming 10% of the radiographs were unreadable. Secondly, in each CVM stage, a stratified quota of 25 children per sex was used, which resulted in 300 children (150 boys, 150 girls), as the minimum calculated was 171. Thirdly, a stratified quota of 25 children per sex each CVM stage was taken (300 children, 150 boys, 150 girls), which is more than the minimum of 171 children calculated. A quota-based sampling strategy was used to obtain balanced representation across the six cervical vertebral maturation stages (CS1-CS6). The sample included 25 male and 25 female participants at each stage, yielding 50 participants per stage and a total sample of 300. This approach facilitated the evaluation of associations between dental calcification stages and CVM across the maturation spectrum. However, the distribution of CVM stages was determined by the sampling design and therefore does not represent their natural distribution in the source population.

The study included eligible radiographic records from July to December 2024. This period was selected based on the availability of records meeting the predefined eligibility criteria and the feasibility of obtaining a consistent dataset for the retrospective analysis. The study duration was determined by the availability of eligible records rather than by an assumption that a longer observation period would necessarily improve the study quality. Written informed consent was obtained from the parents or legal guardians of eligible participants, as applicable.

Inclusion Criteria

Children aged 7-17 years with good-quality lateral cephalograms and panoramic radiographs obtained within one month of each other were eligible for inclusion. Records were excluded if they met any of the exclusion criteria. The inclusion and exclusion criteria used for participant selection are presented in Table *1*.

Inclusion criteria	Exclusion criteria
Children aged 7-17 years	Systemic diseases or syndromes affecting growth
Availability of a good-quality lateral cephalogram	History of head and neck trauma or surgery
Availability of a good-quality panoramic radiograph	Congenitally missing or extracted mandibular canine, first premolar, second premolar, or second molar
Lateral cephalogram and panoramic radiograph obtained within one month of each other	Dental developmental anomalies
Radiographs of adequate diagnostic quality for assessment of the required anatomical structures	Vertebral anomalies
	Previous orthodontic treatment
	Radiographic distortion or inadequate diagnostic quality of the regions of interest

TABLE 1: Inclusion and exclusion criteria for participant selection

Assessment of Skeletal Maturity

Lateral cephalograms were used to assess CVM stage according to Baccetti et al. [5]. The second, third, and fourth cervical vertebrae were examined for concavities at their lower borders and the body shape of the C3 and C4 vertebrae, and each radiograph was scored from CS1 to CS6. CS1 and CS2 represent the prepubertal stage, CS3 and CS4 the pubertal growth spurt, and CS5 and CS6 the postpubertal stage [14].

Dental calcification was assessed by scoring the calcification of the left mandibular canine (33), first premolar (34), second premolar (35), and second molar (37) on panoramic radiographs based on the Demirjian et al. [15] scale. The stage of each tooth was assigned to one of eight stages ranging from A (calcium deposition occurred at the tips of the cusps but not at the apex) to H (apex closed). If the left tooth couldn't be seen, the contralateral tooth was scored instead. For analysis, stages A-H were coded 1-8 [16].

Dental calcification was assessed using the eight-stage Demirjian classification (stages A-H), which categorizes tooth development according to morphological criteria. These stages are ordinal indicators of developmental progression and should not be interpreted as direct estimates of chronological or dental age. The application of this classification should also consider potential population-related variation in dental maturation. Examiner training and consistent application of standardized staging criteria are important to

improve assessment reliability.

The study included eligible radiographic records of children and adolescents aged 7-17 years obtained during July-December 2024. A quota-based sampling strategy was used to include 50 participants at each of the six CVM stages (CS1-CS6), comprising 25 males and 25 females per stage. Records were assessed against the predefined eligibility criteria before inclusion. The sampling frame and quota-based selection process were considered when interpreting the findings, as the resulting sample was not intended to represent the natural distribution of CVM stages in the source population.

Inter-Examiner Reliability

All radiographs were evaluated by one trained examiner, under standardized viewing conditions, and blind to the other radiograph or to the patient's age. Skeletal and dental stages were scored separately. Intra-examiner reliability was assessed by scoring a random 10% sub-sample (n=30) which was re-scored after two weeks, and was expressed using quadratic-weighted Cohen's kappa.

The left mandibular canine, first premolar, second premolar, and second molar were assessed according to the predefined radiographic evaluation protocol. When a tooth on the left side could not be evaluated and the contralateral tooth was substituted, the occurrence of such substitutions was documented. Left-right agreement was assessed only if bilateral measurements were available and a formal comparison had been performed.

Data Analysis

Data were analyzed with SPSS Statistics for Windows, version 26 (IBM Inc., Armonk, NY, USA) and SciPy (Python Software Foundation) using statistical analysis. As CVM and Demirjian stages are ordinal, non-parametric tests were used. Age was summarised as mean ± standard deviation (SD), and dental stages as frequency (%) and median (interquartile range, IQR). The correlation between CVM stage and calcification stage of each tooth was performed using Spearman's rank correlation coefficient (ρ) for boys, girls, and the total sample; 95% confidence intervals (CI) were obtained by Fisher's z transformation of ρ with the Fieller standard error. Correlations were graded as very weak (<0.20), weak (0.20-0.39), moderate (0.40-0.59), strong (0.60-0.79), or very strong (⩾0.80). Fisher's r-to-z test was used to compare male and female coefficients. The Kruskal-Wallis H test was used to compare the dental stage for differences between CVM stages, and the Mann-Whitney U test was used to evaluate differences between sexes within each CVM stage. A p-value of < 0.05 was used as the cut-off point for statistical significance.

The data supporting the findings of this study are available from the corresponding author upon reasonable request, subject to institutional ethical requirements and applicable data-protection restrictions.

Results

The sample comprised 300 children (150 boys, 150 girls) aged 7.0-17.0 years (mean 12.14 ± 2.73 years). Mean age was 12.55 ± 2.65 years in boys and 11.73 ± 2.75 years in girls. Mean age rose steadily from CS1 to CS6 in both sexes, and girls were younger than boys at every stage from CS1 to CS5 (Table *2*). Chronological age was summarized across the six cervical vertebral maturation stages (CS1-CS6) to describe the age distribution of participants at each maturation stage. The age distribution was examined alongside the observed associations between CVM stages and dental calcification stages to contextualize the relationship between chronological age, skeletal maturation, and dental development.

CVM stage	Boys (n)	Girls (n)	Total (n)	Mean age, boys (years)	Mean age, girls (years)	SD of age, total (years)
CS1	25	25	50	8.56	8.16	0.95
CS2	25	25	50	10.87	9.49	1.38
CS3	25	25	50	12.07	11.04	1.41
CS4	25	25	50	13.26	12.52	1.32
CS5	25	25	50	14.84	13.48	1.28
CS6	25	25	50	15.68	15.70	0.91
Total	150	150	300	12.55	11.73	2.73

TABLE 2: Distribution of the sample and mean age by cervical vertebral maturation stage and sex

CVM - cervical vertebral maturation; CS - cervical stage; SD - standard deviation

Intra-examiner reliability was almost perfect for all variables. Quadratic-weighted kappa was 0.978 for CVM stage, 0.961 for the canine, 0.949 for the first premolar, 0.979 for the second premolar, and 0.956 for the second molar, with exact agreement of 73.3%-86.7% (Table *3*).

Variable	Exact agreement (%)	Weighted κ	Interpretation
CVM stage	86.7	0.978	Almost perfect
Mandibular canine (33)	80.0	0.961	Almost perfect
Mandibular first premolar (34)	76.7	0.949	Almost perfect
Mandibular second premolar (35)	86.7	0.979	Almost perfect
Mandibular second molar (37)	73.3	0.956	Almost perfect

TABLE 3: Intra-examiner reliability (n=30, re-scored after two weeks)

CVM - cervical vertebral maturation; κ - quadratic-weighted Cohen's kappa

The calcification stage of all four teeth was positively correlated with CVM stage and was significant in boys, girls, and the total sample ($p<0.001$ for all). The second premolar ($\rho=0.758$) and canine ($\rho=0.756$) were the most strongly correlated with each other, followed by the first premolar ($\rho=0.683$) and second molar ($\rho=0.628$) in the total sample. When examining the correlation between the second premolar and other teeth in boys, it was the most strongly associated tooth and the only tooth in the very strong range ($\rho=0.807$). The canine was first in girls ($\rho=0.763$). In both sexes, the second molar gave the least correlation. There was no significant difference in any of the coefficients between the boys and girls, except for the second premolar, which approached significance ($p=0.055$). CVM stage showed the highest correlation with chronological age, higher than any of the tooth measurements ($\rho=0.897$) (Table *4*).

Tooth	Total (n=300), ρ (95% CI)	Boys (n=150), ρ (95% CI)	Girls (n=150), ρ (95% CI)	Sex difference, z	Sex difference, p-value
Mandibular canine (33)	0.756 (0.701-0.802)	0.751 (0.669-0.815)	0.763 (0.684-0.824)	-0.221	0.825
Mandibular first premolar (34)	0.683 (0.615-0.740)	0.641 (0.532-0.729)	0.722 (0.633-0.793)	-1.274	0.203
Mandibular second premolar (35)	0.758 (0.704-0.804)	0.807 (0.740-0.858)	0.710 (0.617-0.783)	1.920	0.055
Mandibular second molar (37)	0.628 (0.551-0.693)	0.600 (0.483-0.696)	0.657 (0.552-0.742)	-0.787	0.431
Chronological age (reference)	0.897 (0.872-0.918)	0.903 (0.867-0.929)	0.913 (0.881-0.937)	-	-

TABLE 4: Spearman rank correlation between CVM stage and Demirjian calcification stage, with comparison between sexes

All individual Spearman rank correlation coefficients were statistically significant ($p < 0.001$). The p-values in the final column represent comparisons of correlation coefficients between boys and girls using Fisher's r-to-z test.

CVM - cervical vertebral maturation; ρ - Spearman's rank correlation coefficient; CI - confidence interval

All the correlation coefficients were $p<0.001$. Fisher's r-to-z test was used for sex differences. The median calcification stage for each tooth increased with CVM stage and was significant between CVM stages (Kruskal-Wallis, $p<0.001$). The canine moved from stage C at CS1 to stage H at CS6, and the second premolar from stage C to stage G. During the pubertal peak (CS3-CS4), the median stage was F for the canine and first premolar, E-F for the second premolar, and E for the second molar (Table *5*).

Tooth	CS1	CS2	CS3	CS4	CS5	CS6	Kruskal-Wallis H	p-value
Mandibular canine (33)	C (3-5)	E (4-5)	F (5-6)	F (5-7)	F (6-7)	H (7-8)	172.60	<0.001
Mandibular first premolar (34)	D (4-5)	E (4-6)	F (5-6)	F (5-6)	F (6-7)	H (6-8)	142.15	<0.001
Mandibular second premolar (35)	C (3-4)	D (4-5)	E (4-6)	F (5-6)	F (6-7)	G (6-8)	173.60	<0.001
Mandibular second molar (37)	C (2-4)	D (3-5)	E (4-6)	E (4-6)	F (5-6)	G (6-8)	121.64	<0.001

TABLE 5: Median (IQR) Demirjian stage at each CVM stage

Values are median stage letters with IQR as numeric codes (A=1 to H=8); df=5.

IQR - interquartile range; CVM - cervical vertebral maturation; CS - cervical stage

At the pubertal growth peak (CS3 and CS4 combined), the mandibular canine was most often at stage E in boys (42%) and at stage F in girls (44%). Stages E, F, and G together accounted for 86% of boys and 82% of girls in this phase (Table *6*).

Sex	n	Stage C, n (%)	Stage D, n (%)	Stage E, n (%)	Stage F, n (%)	Stage G, n (%)	Stage H, n (%)
Boys	50	2 (4)	4 (8)	21 (42)	12 (24)	10 (20)	1 (2)
Girls	50	0 (0)	6 (12)	12 (24)	22 (44)	7 (14)	3 (6)

TABLE 6: Distribution of mandibular canine calcification stages at the pubertal growth peak (CS3 + CS4)

No child was at stage A or B during CS3-CS4.

CS - cervical stage

Within each CVM stage, dental calcification stages did not differ significantly between boys and girls for the canine, first premolar, or second premolar (Mann-Whitney U, p>0.05). The only significant sex difference was for the second molar at CS6 (p=0.038) (Table 7). Positive correlations were observed between CVM stages and dental calcification stages across all four mandibular teeth. The strongest correlations were observed for the second premolar (Spearman's ρ = 0.758; 95% CI: 0.704-0.804) and canine (ρ = 0.756; 95% CI: 0.701-0.802), followed by the first premolar (ρ = 0.683; 95% CI: 0.615-0.740). The second molar demonstrated a comparatively weaker, although positive, correlation (ρ = 0.628; 95% CI: 0.551-0.693).

Tooth	CS1	CS2	CS3	CS4	CS5	CS6
Mandibular canine (33)	0.391	0.177	0.069	0.928	0.657	0.352
Mandibular first premolar (34)	0.336	0.425	0.760	0.206	0.618	0.446
Mandibular second premolar (35)	0.677	0.960	0.291	0.746	0.069	0.559
Mandibular second molar (37)	0.984	0.546	0.644	0.317	0.920	0.038*

TABLE 7: Comparison of Demirjian stage between boys and girls within each CVM stage (Mann-Whitney U test, p-values)

*p<0.05

CVM - cervical vertebral maturation; CS - cervical stage

Although the correlation coefficients varied descriptively between males and females, none of the sex-related comparisons reached statistical significance. The p-values for the comparisons were 0.825 for the canine, 0.203 for the first premolar, 0.055 for the second premolar, and 0.431 for the second molar.

Discussion

The null hypothesis was rejected because this study revealed strong and significant relationships between cervical vertebral maturation and all four mandibular teeth studied, which were the calcification stages. There was a higher correlation between the second premolar and the canine, followed by the first premolar and the second molar. These results indicate that an X-ray of the whole mouth can provide useful information about a child's skeletal maturity.

Previous studies have reported associations between dental calcification stages and skeletal maturation indicators. The present findings similarly demonstrate positive correlations between Demirjian calcification stages and cervical vertebral maturation stages, although the strength of association varies among the evaluated teeth. These correlations reflect a relationship between ordinal developmental stages and should not be interpreted as numerical agreement between dental age and skeletal age [14], and Coutinho et al. [10] have found a close relationship between the development of the canine and skeletal maturity indicators. Correlations between the same factors were reported for children with values similar to those found in a previous study by Minervini [15]. The range of our coefficients is similar, confirming the consistency of the dental-skeletal relationship in different populations despite the different order of the teeth used in the different studies.

The weakest correlation with cervical vertebral maturation was observed for the mandibular second molar in

both boys (ρ = 0.600) and girls (ρ = 0.657). This is contrary to the second molar, which Kumar et al. suggested as a practical indicator of skeletal maturity in Indian children [15]. The second molars begin to calcify throughout the circumpubertal period from before until after puberty, and there is significant individual variation. The interquartile ranges for the second molars were very similar for CS2 and CS4, and this diminishes its usefulness in distinguishing pre-peak from peak stages in our data [17].

Sex differences were small but present. The second premolar was the highest-ranking tooth for boys, and the canine for girls, and there was no significant difference between the coefficients for boys and girls. In each skeletal stage, dental stages were also similar in boys and girls, except for the dental stage 2 molar at CS6. Girls achieved each skeletal stage at a younger age than boys because of early puberty. A single stage-tooth reference may apply to both dental and CVM stages, as there was no difference between the two developmental stages in both sexes, although the most typical pubertal peak was E in boys and F in girls [18].

There was a better correlation between chronological age and CVM stage than with any single tooth (ρ=0.897). This is partly due to the stratified sample, as ages are evenly distributed for CS1 to CS6. Dental maturity has been found to be only loosely correlated with somatic maturity and skeletal maturity [19]. Rozylo-Kalinowska et al. reported a relationship between dental and skeletal age, but not between ages [20]. Therefore, dental calcification stages should only be used as a screening tool and not as a replacement for skeletal assessment.

The mandibular second molar demonstrated a comparatively weaker correlation with CVM stage (Spearman's ρ = 0.628; 95% CI: 0.551-0.693) than the canine and second premolar. Overlapping interquartile ranges may further limit the ability to distinguish individual maturation stages based on dental calcification alone. Therefore, the second molar should not be considered a preferred standalone indicator of skeletal maturation based on these findings. Its potential clinical utility requires further evaluation using diagnostic performance measures and representative study populations.

At the pubertal growth peak (CS3-CS4), stage E was the most frequent mandibular canine calcification stage in boys (21/50, 42%), whereas stage F predominated in girls (22/50, 44%). Stages E, F, and G together accounted for 43/50 (86%) boys and 41/50 (82%) girls. These findings suggest that mandibular canine calcification may provide a useful supplementary indicator of pubertal skeletal maturation.

The possible use of dental calcification stages as a supplementary indicator should be considered hypothesis-generating. The present cross-sectional study evaluated associations rather than diagnostic performance and therefore cannot establish the ability of dental calcification to classify skeletal maturity accurately in individual patients.

Chronological age is an important consideration when interpreting the observed associations because both dental calcification and cervical vertebral maturation progress with age. Consequently, the unadjusted correlations may partly reflect shared age-related development rather than an independent relationship between the two maturation indicators. Chronological age may also provide substantial information about skeletal maturation. Because age-adjusted associations and comparative predictive performance were not established, the present findings do not demonstrate that dental calcification provides additional predictive information beyond chronological age.

Although panoramic radiographs may provide information about both dental calcification and skeletal maturation, their acquisition involves ionizing radiation. The potential benefit of assessing dental calcification therefore relates to extracting supplementary information from an existing radiograph rather than using a radiation-free method. Further validation in representative populations, including assessment of sensitivity, specificity, and classification accuracy, is necessary before dental calcification can be recommended as a screening approach for skeletal maturity.

Limitations

There are several limitations in this study. The cross-sectional design does not allow for tracking children as they go through the growth spurt, and the timing relationship should be tested in longitudinal studies. Quota sampling (equal numbers/sex and stage) will not accurately reflect the actual distribution of stages in the population and may overestimate correlation coefficients. The inter-examiner reliability was not assessed, and all radiographs were scored by the same examiner, both of which are factors that could affect CVM staging, as the staging of CVM is known to vary from examiner to examiner. Lastly, the sample was drawn from a single site and may not be representative of other groups. The quota-based sampling strategy ensured balanced representation across CVM stages and sex but limited the representativeness of the study sample. Because participants were selected to achieve predefined quotas, the observed stage frequencies cannot be interpreted as population prevalence estimates. Furthermore, conditioning sample selection on CVM stage may influence the observed association between dental calcification and skeletal maturation. Therefore, the correlation estimates should be interpreted within the context of the sampling design and validated in representative populations. The analyses primarily evaluated unadjusted associations between dental calcification stages and CVM stages. Because both measures are related to chronological age, the

observed correlations may partly reflect their shared age-related progression. The absence of age- and sex-adjusted estimates limits the interpretation of the independent association between dental calcification and skeletal maturation.

Cervical vertebral maturation staging involves visual interpretation of vertebral morphology and may be affected by examiner experience and variability in stage assignment. Although the present study demonstrated high intra-examiner reliability (weighted $\kappa = 0.978$), staging was performed by a single examiner; therefore, inter-examiner reproducibility could not be assessed. Examiner calibration using standardized staging criteria and independent assessments by multiple trained examiners are important to establish the reproducibility of CVM classification. Future studies should incorporate examiner calibration and inter-examiner agreement analyses to determine whether the observed associations can be reproduced across assessors.

Although intra-examiner reliability was high, with weighted kappa values ranging from 0.949 to 0.979, inter-examiner reliability was not assessed. Consequently, the reproducibility of CVM staging and dental calcification scoring between different examiners remains uncertain. Future studies should include at least two calibrated, blinded examiners and report inter-examiner agreement to strengthen the reproducibility of these assessments.

Conclusions

CVM stages were correlated strongly and positively with the calcification stages of the second molar, second premolar, first premolar, and mandibular canine teeth in this pediatric sample. The strongest relationships were between the second premolar and the canine, while the weakest were between the second molar. There were no significant differences between boys and girls in the correlations. Dental calcification stages, when assessed on panoramic X-rays, can be a simple, radiation-saving screening method to identify children who may be entering the pubertal growth spurt. When precise timing of orthopedic treatment is needed, they should be used in conjunction with, rather than as a substitute for, the use of skeletal maturity indicators.

Dental calcification stages demonstrated positive associations with cervical vertebral maturation stages, with variation in correlation strength among the evaluated mandibular teeth. However, these findings do not establish diagnostic accuracy or demonstrate that dental calcification can replace established skeletal maturity assessment methods. Further studies using representative populations, age-adjusted analyses, and diagnostic performance measures are required before clinical application can be recommended.

Additional Information

Author Contributions

All authors have reviewed the final version to be published and agreed to be accountable for all aspects of the work.

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Disclosures

Human subjects: Informed consent for treatment and open access publication was obtained or waived by all participants in this study. Institutional Ethical Committee of Vyas Dental College and Hospital issued approval VDCH/IEC/2024/10. **Animal subjects:** All authors have confirmed that this study did not involve animal subjects or tissue. **Conflicts of interest:** In compliance with the ICMJE uniform disclosure form, all authors declare the following: **Payment/services info:** All authors have declared that no financial support was received from any organization for the submitted work. **Financial relationships:** All authors have declared that they have no financial relationships at present or within the previous three years with any organizations that might have an interest in the submitted work. **Other relationships:** All authors have declared that there are no other relationships or activities that could appear to have influenced the submitted work.

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