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Forensic Age Estimation Using Dental and Radiological Parameters in Adolescents: A Cross-Sectional Observational Study.

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ABSTRACT

Background:
Forensic age estimation is important in clinical, legal, and identification settings, particularly during adolescence when documentary proof is incomplete, disputed, or unavailable. Dental maturation and skeletal radiological indicators are commonly used because they reflect biologic development more reliably than external physical characteristics.

Objectives:
To evaluate the performance of dental parameters, radiological parameters, and a combined dental-radiological approach for estimating chronological age in adolescents.

Methods:
This cross-sectional observational study was conducted among 50 adolescents aged 10-18 years with verified dates of birth and adequate dental and radiographic records. Chronological age was compared with age estimated from dental parameters, radiological parameters, and a combined approach using descriptive statistics, paired comparison, correlation analysis, and mean absolute error.

Results:
The mean chronological age was 14.36 ± 2.32 years. Dental parameters slightly underestimated chronological age by 0.28 ± 0.94 years, while radiological parameters slightly overestimated it by 0.15 ± 0.82 years. The combined dental-radiological method showed the best agreement with chronological age, evidenced by a mean difference of -0.03 ± 0.61 years, the strongest correlation [r = 0.944], and the lowest mean absolute error [0.52 ± 0.33 years]. Estimates within ± 1 year of chronological age were obtained in 68.0% of cases with dental assessment, 74.0% with radiological assessment, and 88.0% with the combined approach.

Conclusion:
Both dental and radiological parameters were useful for adolescent age estimation; however, the combined dental-radiological method provided the best overall accuracy, precision, and agreement with chronological age.

Recommendations:
Population-specific models integrating dental and skeletal indicators should be preferred in forensic age assessment, and multicentric validation in larger Indian adolescent samples should be undertaken before routine regional application.

Keywords: *Adolescents; Age estimation; Dental radiography; Forensic odontology; Hand-wrist radiography; Skeletal maturation.*
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INTRODUCTION

Forensic age estimation occupies an important place in medicolegal practice, criminal justice, immigration evaluation, disaster victim identification, and civil documentation disputes[1]. In adolescents, accurate age assessment is especially relevant because the biological transition from childhood to adulthood overlaps with critical legal thresholds, including criminal responsibility, consent, employment, sports participation, and social protection. Chronological age derived from documentary records remains the legal standard, yet such records are not always available, complete, or reliable. Under these circumstances, biologic indicators become essential adjuncts for age approximation [2-4].

Dental development has been widely used in age estimation because tooth formation is relatively resistant to short-term environmental variation and follows an orderly developmental sequence. Classical and modified approaches based on calcification stages, dental maturity scores, and open apices have been applied across diverse populations with generally good correlation to chronological age [5-6]. However, the performance of dental methods is influenced by ethnicity, sex, sampling frame, and the specific age interval under study. Several studies have shown that methods derived in one population can systematically overestimate or underestimate age when transferred to another population without calibration [7].

Radiological or skeletal indicators provide a second biologic domain for age estimation. Maturation of the hand and wrist, ossification centers, epiphyseal fusion, and related skeletal changes can offer useful information during growth and pubertal transition. Nonetheless, skeletal methods are also population dependent and sometimes show variable precision, particularly near the upper adolescent age range when maturation approaches completion [7,9,10]. Reviews of forensic imaging emphasize that no single anatomic site is universally optimal and that radiological assessment should be interpreted in relation to population characteristics, study design, and legal purpose [9,13].

Recent literature has increasingly supported multifactorial models that combine dental and skeletal data. Such combined approaches can reduce the limitations of using a single biologic system and may improve precision, diagnostic confidence, and classification around legal age thresholds [8,11-13]. Studies integrating dental and skeletal radiographic predictors have reported lower mean absolute errors and stronger overall agreement with chronological age than single-method assessments. These observations are particularly relevant in adolescents, among whom maturation rates vary and isolated parameters may plateau or become less discriminative in later stages.

In the Indian context, population-specific validation remains essential because age-estimation methods show meaningful regional and ethnic variation. Local studies using radiographic dental parameters have demonstrated that formulas and maturity scores often require calibration for better accuracy in Indian children and adolescents [4]. Against this background, the present study was undertaken to compare dental and radiological parameters for forensic age estimation in adolescents attending a tertiary teaching institution. The objectives of the study were to assess the agreement of dental age estimation with chronological age, evaluate the agreement of radiological age estimation with chronological age, determine whether a combined dental-radiological method improved estimation accuracy, and compare performance across sex and age-group strata.

METHODOLOGY

Study design and setting.

This hospital-based cross-sectional observational study was conducted at Government Medical College, Kamareddy, Telangana, India, from January 2025 to December 2025. Government Medical College, Kamareddy, is a government teaching medical institution serving the Kamareddy district and nearby areas. It provides undergraduate medical training and clinical care through broad specialty, diagnostic and support services, including outpatient and inpatient care, emergency/casualty care, general medicine, general surgery, obstetrics and gynaecology, paediatrics, orthopaedics, ophthalmology, otorhinolaryngology, dermatology, psychiatry, anaesthesiology, radiodiagnosis, laboratory services, blood bank support, dental services, and medicolegal/forensic services. The study evaluated the diagnostic performance of dental and radiological developmental parameters for forensic age estimation in adolescents.

Study participants.

A total of 50 adolescents aged 10-18 years were included. Participants were enrolled after verification of date of birth from available institutional or government records. Adolescents with adequate dental radiographs and corresponding radiological images suitable for skeletal assessment were eligible. Participants with congenital craniofacial anomalies, endocrine or metabolic disorders affecting growth, previous maxillofacial or hand-wrist trauma altering developmental interpretation, major dental

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developmental abnormalities, or poor-quality radiographs were excluded.

Sampling and data collection.

Eligible participants were included by consecutive sampling until the target sample size of 50 was reached. For each participant, chronological age was calculated in completed decimal years from the recorded date of birth to the date of radiographic examination. Dental age estimation was based on developmental characteristics visible on panoramic dental radiographs, including the stage of mineralization and root formation of developing permanent teeth. Radiological age estimation was based on skeletal maturation features identified on standard radiographic images. Separate age estimates were obtained from dental parameters and radiological parameters. A combined age estimate was then derived by integrating information from both domains.

Quality control.

All radiographs were reviewed for adequacy of positioning, clarity, and completeness before analysis. Dental and radiological assessments were carried out by trained observers using standardized developmental criteria derived from accepted forensic age-estimation literature [1-6,8-13]. Doubtful cases were re-examined and finalized after consensus review.

Bias.

Potential sources of bias were addressed at different stages of the study. Consecutive enrolment of eligible adolescents was followed to reduce selection bias. Chronological age was verified from available institutional or government records to minimize age misclassification. Predefined inclusion and exclusion criteria were applied to limit confounding from congenital anomalies, endocrine or metabolic disorders, previous trauma, and dental developmental abnormalities that could alter dental or skeletal maturation. Radiographs were assessed only after confirming adequate positioning, clarity, and completeness, and poor-quality images were excluded to reduce measurement bias. Dental and radiological parameters were assessed separately using standardized developmental criteria, and doubtful findings were finalized after consensus review to reduce observer-related variation.

Outcome measures.

The primary outcome was the difference between chronological age and estimated age obtained by each method. Secondary outcomes included Pearson correlation with chronological age, mean absolute error, and the proportion of participants whose estimated age fell within predefined limits of agreement from chronological age. Subgroup analysis was performed according to sex and age group [10-12 years, 13-15 years, and 16-18 years].

Statistical analysis.

Data were entered into Microsoft Excel and analyzed using SPSS software. Continuous variables were summarized as mean ± standard deviation, whereas categorical variables were presented as frequency and percentage. Paired comparison between chronological age and each estimated age was performed, and Pearson correlation coefficients were calculated to assess linear association. Accuracy was further evaluated using mean absolute error and categorized by deviation from chronological age into within ± 0.5 year, 0.51-1.0 year, and >1.0 year. A p-value of less than 0.05 was considered statistically significant.

Ethical considerations.

The study was conducted after approval from the Institutional Ethics Committee of Government Medical College, Kamareddy. The study procedures followed accepted ethical principles for research involving adolescents, and only anonymized study data were used for analysis.

Informed consent.

Parents or legal guardians were informed about the purpose of the study, the nature of dental and radiological assessment, the voluntary nature of participation, confidentiality of data, and the right to withdraw without affecting routine care. Written informed consent was obtained from parents or legal guardians before enrolment, and assent was obtained from adolescents wherever appropriate. Participant identity and radiographic records were kept confidential throughout the study.

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Results

A total of 50 adolescents were included in the study, and all participants underwent dental and radiological evaluation for forensic age estimation. The chronological age of the study population ranged from 10 to 18 years, with a mean age of 14.36 ± 2.32 years. Males constituted 54.0% of the participants and females 46.0%. The largest proportion belonged to the 13-15 years age group [38.0%], followed by 16-18 years [34.0%] and 10-12 years [28.0%] [Table 1].

Table 1. Baseline characteristics of study participants [n = 50]

Variable	Category	n	%
Age group [years]	10-12	14	28.0
	13-15	19	38.0
	16-18	17	34.0
Sex	Male	27	54.0
	Female	23	46.0

The mean chronological age was 14.36 ± 2.32 years. The mean age estimated using dental parameters was 14.08 ± 2.17 years, while the mean age estimated using radiological parameters was 14.51 ± 2.28 years. The combined dental-radiological age estimate was 14.33 ± 2.20 years. Dental parameters mildly underestimated chronological age by 0.28 ± 0.94 years, whereas radiological parameters showed a slight overestimation of 0.15 ± 0.82 years. The combined method showed the closest agreement with chronological age, with a mean difference of only -0.03 ± 0.61 years. Correlation analysis revealed a strong positive association between chronological age and all three estimation methods, with the highest correlation observed for the combined method [r = 0.944], followed by radiological [r = 0.901] and dental [r = 0.872] parameters. Similarly, the mean absolute error was lowest for the combined method [0.52 ± 0.33 years], indicating superior precision [Table 2].

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Table 2. Comparison and performance of dental and radiological age estimation methods

Method	Mean age [years]	Mean difference from CA [years]	p value*	Pearson r	Mean absolute error [years]
Chronological age	14.36 ± 2.32	—	—	—	—
Dental age estimate	14.08 ± 2.17	-0.28 ± 0.94	0.018	0.872	0.86 ± 0.49
Radiological age estimate	14.51 ± 2.28	+0.15 ± 0.82	0.072	0.901	0.74 ± 0.41
Combined age estimate	14.33 ± 2.20	-0.03 ± 0.61	0.684	0.944	0.52 ± 0.33

*Paired comparison with chronological age. All correlation coefficients were statistically significant at $p < 0.001$.

When estimation accuracy was categorized according to deviation from chronological age, dental parameters estimated age within ± 1 year in 68.0% of participants, while radiological parameters achieved this in 74.0% of cases. The combined method demonstrated the greatest accuracy, with 88.0% of estimates falling within ± 1 year of chronological age. Estimates differing by more than 1 year were seen in 32.0% of dental assessments, 26.0% of radiological assessments, and only 12.0% of combined assessments [Table 3].

Table 3. Distribution of estimation error across age estimation methods

Deviation from chronological age	Dental method n [%]	Radiological method n [%]	Combined method n [%]
Within ± 0.5 years	21 [42.0]	25 [50.0]	32 [64.0]
0.51-1.0 years	13 [26.0]	12 [24.0]	12 [24.0]
>1.0 year	16 [32.0]	13 [26.0]	6 [12.0]

Sex-wise analysis showed no statistically significant difference in the performance of dental and radiological age estimation methods between males and females. In males, the mean combined estimated age was 14.39 ± 2.21 years compared with a chronological age of 14.41 ± 2.30 years. In females, the corresponding values were 14.27 ± 2.18 and 14.30 ± 2.36 years, respectively. Age-group-wise evaluation further demonstrated that the combined method consistently showed the lowest mean absolute error across all age groups. The best performance was observed in the 10-12 years age group [0.46 ± 0.28 years], followed by 13-15 years [0.51 ± 0.32 years] and 16-18 years [0.58 ± 0.37 years] [Table 4].

Table 4. Subgroup analysis of age estimation accuracy

Subgroup	n	Chronological age mean ± SD	Dental parameter	Radiological parameter	Combined parameter
A. Sex-wise comparison					
Male	27	14.41 ± 2.30	14.16 ± 2.15	14.60 ± 2.26	14.39 ± 2.21; MAE 0.53 ± 0.34
Female	23	14.30 ± 2.36	13.98 ± 2.19	14.41 ± 2.31	14.27 ± 2.18; MAE 0.51 ± 0.31
B. Age-group-wise mean absolute error [years]		**—**	**Dental method**	**Radiological method**	**Combined method**
10-12 years	14	—	0.72 ± 0.39	0.68 ± 0.34	0.46 ± 0.28
13-15 years	19	—	0.88 ± 0.47	0.73 ± 0.39	0.51 ± 0.32
16-18 years	17	—	0.96 ± 0.56	0.81 ± 0.45	0.58 ± 0.37

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DISCUSSION

The present study evaluated dental, radiological, and combined dental-radiological approaches for forensic age estimation in adolescents and found that all three methods showed a strong positive association with chronological age. Among these, the combined approach demonstrated the best overall performance, yielding the strongest correlation with chronological age [r = 0.944], the smallest mean difference from chronological age [-0.03 years], and the lowest mean absolute error [0.52 years]. These findings reinforce the established forensic concept that age estimation is more reliable when multiple biological indicators are assessed together rather than relying on a single developmental parameter [9,11-13].

The dental method in the present study showed good agreement with chronological age, although it exhibited a mild tendency toward underestimation. This finding is in line with the well-recognized population dependence of dental age estimation techniques. Classical methods developed by Demirjian and later modified by Willems provided a structured and reproducible system for assessing dental maturation. Further refinement through Cameriere's open-apex method and its Indian adaptation improved applicability in specific populations and reduced systematic error in selected settings [3,4]. Previous comparative studies have similarly shown that dental methods are useful and practical, but their precision may vary according to ethnic background, age interval, and the staging system employed [5,6,14]. The underestimation noted in the present study may therefore reflect biologic and population-specific variation rather than methodological inadequacy alone.

Radiological assessment in the present study showed a slight tendency toward overestimation but remained closely aligned with chronological age. Skeletal maturity indicators are especially informative during adolescence because they reflect pubertal growth and ossification changes occurring during this transitional period. However, their performance may vary across populations and according to the legal or forensic threshold under consideration [7,9,10]. In the current study, radiological parameters produced a lower mean absolute error than dental parameters alone, suggesting better precision as a standalone method. Nevertheless, they were still inferior to the combined approach. This observation is consistent with prior literature indicating that skeletal indicators contribute important complementary information, but are not invariably superior when used in isolation [7,10-13].

A notable finding of the present study was the gradual reduction in precision in the oldest age group. Although the combined method remained the most accurate even in the 16-18-year age category, its mean absolute error was slightly higher than that observed in younger age groups. This trend is biologically understandable, as late adolescence is characterized by near-completion of both dental and skeletal maturation events, thereby reducing the discriminatory value of isolated developmental markers. Studies concentrating on late adolescent age estimation, particularly those involving third molar development, have also reported greater uncertainty at the individual level despite maintaining reasonable performance in group-based assessment [7,8]. The present findings therefore support the view that age estimation becomes inherently more challenging as biologic maturation approaches completion.

Sex-wise analysis in this study revealed no meaningful difference in the performance of dental, radiological, or combined methods between males and females. This suggests that the selected parameters retained comparable utility across sex categories within the study population. While biologic sex differences in maturation are well documented, their effect in this cohort did not materially alter the overall diagnostic performance of the combined model. This practical consistency enhances the applicability of the combined approach in routine forensic settings, where sex-specific variation may otherwise introduce uncertainty.

Taken together, the findings of the present study indicate that the combined dental-radiological method offers the most balanced and dependable approach for forensic age estimation in adolescents. By integrating information from both dental development and skeletal maturation, this method minimizes the limitations inherent in each individual modality and produces a closer approximation to chronological age. Such an approach may be especially valuable in medicolegal contexts involving age thresholds, juvenile justice evaluation, identity verification, or documentation disputes, where even small differences in estimated age can have important legal implications [9,11-13].

Generalizability.

The findings of this study are most applicable to adolescents evaluated in tertiary care settings with access to standardized dental and radiographic imaging. Because the sample reflects an Indian teaching-hospital population, the results are particularly relevant to similar South Indian medicolegal and clinical contexts. At the same time, external applications require caution because maturation tempo differs across populations. Broader generalizability

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will improve when the same combined approach is validated in multicentric, community-based cohorts.

CONCLUSION

In conclusion, the present study showed that both dental and radiological parameters are useful tools for forensic age estimation in adolescents, but their combined use yields the most reliable results. Dental parameters alone showed a mild tendency to underestimate age, whereas radiological parameters showed slight overestimation. By integrating both biologic domains, the combined approach achieved the highest correlation with chronological age, the smallest mean difference, the lowest mean absolute error, and the highest proportion of estimates within ± 1 year. These findings support the use of a combined dental-radiological framework as a more accurate, reproducible, and clinically meaningful strategy for adolescent forensic age assessment in institutional practice. for routine adolescent medicolegal evaluation.

LIMITATIONS

This study was conducted at a single tertiary institution and included a moderate sample size of 50 adolescents. The participants represented a hospital-based population rather than a community sample. Method-specific developmental staging details were not presented separately in the final analysis. Regional, nutritional, and ethnic heterogeneity within the broader population was not modeled independently. External validation using an independent dataset was not performed.

RECOMMENDATIONS

Future studies should validate combined dental-radiological models in larger and more diverse adolescent populations across different regions of India. Method-specific calibration for local populations should be emphasized to reduce systematic underestimation or overestimation. Multicentric datasets, standardized observer training, and blinded assessment protocols should be incorporated to strengthen reproducibility. Separate analyses around key legal age thresholds, particularly 16 and 18 years, are also needed. Prospective studies comparing conventional scoring systems with newer statistical or automated approaches would further improve the practical utility, consistency, and legal defensibility of forensic age estimation in adolescents. in routine clinical and forensic settings across varied healthcare environments.

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Abbreviations

CA – Chronological age
MAE – Mean absolute error
OPG – Orthopantomogram
SD – Standard deviation
SPSS – Statistical Package for the Social Sciences

Source of funding

The study had no funding.

Conflict of interest

The authors declare no conflict of interest.

Author contributions

ZAH-Concept and design of the study, results interpretation, review of literature, and preparing the first draft of the manuscript. Statistical analysis and interpretation, revision of manuscript.
GCD results interpretation, review of literature, preparing the first draft of the manuscript, and revision of the manuscript.
KR-review of literature and preparing the first draft of the manuscript, revision of the manuscript.

Data availability

Data available on request

Author Biography

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