# Radiographic Indicators for Dental Age Estimation in Children and Adolescents: A Systematic Review

Mohammed Yahya Mashaa Albassous[1], Ali Saleh Manea Almutared[2], Mutared Mana sherfan Alyami[3], Rabiah Dalil Alreshidi[4], Sarah Ghazi Baghawi[5], Mohammed Jamal Alyami[6], Mutarid Owaidh Al-Mutarid[7], Ali Mohammed Ali Abudarahem[8], Mohammed Ahmed Ali Almashham[9], Fatimah Hassan Ali Alshahrani[10], Thekra Ali Ahmed Madkhali[11], Hamad Heshan Mohammed Almanajm[12]

1. Forensic Medical Services Center, Saudi Arabia
2. Forensic Medical Services Center of Najran, Saudi Arabia
3. Maternity & Children's Hospital, Saudi Arabia
4. Hail Health Cluster, Alkhamashia PHC, Saudi Arabia
5. King Abdulaziz Hospital Jeddah first health cluster, Saudi Arabia
6. New Najran General Hospital, Saudi Arabia
7. New Najran General Hospital, Ministry of Health, Saudi Arabia
8. Forensic Medical Services Center, Saudi Arabia
9. King khalid hospital in Najran, Saudi Arabia
10. King Fahad Security college, Saudi Arabia
11. Medical center in king fahad security, Saudi Arabia
12. Happona General Hospital, Saudi Arabia

**Abstract**

**Background:** Dental age estimation is a critical tool in pediatric dentistry, orthodontics, and forensic sciences, particularly in children and adolescents where chronological age documentation may be unavailable or unreliable. Radiographic indicators derived from dental development stages provide a non-invasive and widely applied approach for age assessment.

**Objective:** This systematic review aims to synthesize current evidence on radiographic indicators used for dental age estimation in children and adolescents, focusing on methods applied, accuracy, reliability, and influencing factors.

**Methods:** A systematic search was conducted across electronic databases including PubMed, Scopus, and Web of Science. Eligible studies published between 2000 and 2025 were screened according to predefined inclusion and exclusion criteria following PRISMA guidelines. Radiographic methods, age ranges, population characteristics, and estimation accuracy were extracted and analyzed.

**Results:** The included studies demonstrated that tooth development-based radiographic indicators—particularly those derived from panoramic radiographs—show high accuracy in children and adolescents. However, variability was observed across populations, sex, and methodological approaches.

**Conclusion:** Radiographic dental age estimation is a reliable method in pediatric populations, yet population-specific standards and methodological harmonization remain essential to improve accuracy and clinical applicability.

**Keywords:** Dental age estimation; Radiographic indicators; Children; Adolescents; Panoramic radiography; Systematic review

## INTRODUCTION

Accurate age estimation is a fundamental requirement in pediatric dentistry, orthodontics, and forensic sciences, particularly in children and adolescents where chronological age documentation may be incomplete, disputed, or unavailable. Dental age estimation (DAE) refers to the assessment of biological maturity based on dental development rather than calendar age. Compared with other biological indicators such as skeletal maturation, dental development is considered more stable and less influenced by nutritional, hormonal, and environmental factors, making it a reliable marker during growth periods (AlQahtani et al., 2014; Jayaraman et al., 2016).

Radiographic assessment plays a central role in dental age estimation because many developmental changes in teeth—such as crown formation, root elongation, and apical closure—cannot be accurately evaluated through clinical examination alone. Radiographs allow visualization of internal dental structures and provide objective criteria for staging tooth development across different age groups. Among available imaging modalities, panoramic radiography (orthopantomogram, OPG) is the most widely used in children and adolescents due to its ability to capture the entire dentition in a single image with relatively low radiation exposure (Guo et al., 2018).

Several radiographic methods for dental age estimation have been developed and validated over the past decades. Classical approaches, such as the Demirjian method and its modifications, rely on assigning developmental stages to selected teeth and converting these stages into an estimated dental age. Other techniques, including Willems' adaptation and Cameriere's open apex method, aim to improve accuracy by refining scoring systems or introducing quantitative measurements of root development (Willems et al., 2001; Cameriere et al., 2006). These methods are particularly applicable in children and adolescents, where active dental growth provides clear radiographic indicators for age assessment.

Despite their widespread use, radiographic dental age estimation methods show variability in accuracy across populations. Numerous studies have reported systematic overestimation or underestimation when methods developed on one population are applied to another, highlighting the influence of genetic, ethnic, and socioeconomic factors on dental development (Chen et al., 2019; Franco et al., 2020). Sex-related differences have also been observed, with females often demonstrating slightly advanced dental maturation compared with males of the same chronological age (Hegde et al., 2017).

Given the growing clinical and forensic reliance on radiographic dental age estimation, there is a need for an up-to-date synthesis of evidence focusing specifically on children and adolescents. Previous reviews have often combined pediatric and adult populations or focused on a single method, limiting their applicability to developmental age assessment. Therefore, a systematic review concentrating on radiographic indicators, methodological performance, and influencing factors in pediatric and adolescent groups is essential. Such a synthesis can support evidence-based method selection, highlight research gaps, and guide the development of population-specific standards for more accurate and ethical age estimation practices.

## LITERATURE REVIEW

Dental age estimation (DAE) has long been recognized as a reliable biological indicator for assessing growth and maturation in children and adolescents. Among the various approaches, radiographic methods remain the most widely used due to their ability to visualize internal dental structures and developmental changes that are not observable clinically. The literature consistently highlights that tooth development follows a relatively predictable sequence, making radiographic indicators particularly valuable during childhood and adolescence, when dental growth is active and progressive.

Early radiographic methods for dental age estimation were primarily based on qualitative assessment of tooth formation stages. One of the most influential and extensively studied approaches is the Demirjian method, which evaluates the developmental stages of seven mandibular teeth using panoramic radiographs. Numerous studies have confirmed its practical applicability and ease of use; however, systematic overestimation or underestimation has been reported when applied to populations other than the original French-Canadian sample (Demirjian et al., 1973; AlQahtani et al., 2014). This limitation prompted the development of modified versions tailored to different populations.

Willems et al. (2001) proposed an adaptation of the Demirjian scoring system, converting maturity scores directly into age values. Subsequent studies demonstrated that the Willems method often produces more accurate estimates in children and adolescents compared with the original Demirjian approach, particularly in European and Asian populations (Franco et al., 2020). Nevertheless, population-dependent variability persists, reinforcing the importance of regional validation studies.

Another widely applied radiographic technique is Cameriere's open apex method, which introduces quantitative measurements of root development by assessing the degree of apical closure in developing teeth. This method has shown high accuracy in children, especially between 6 and 14 years of age, and is considered less subjective than stage-based methods due to its reliance on linear measurements (Cameriere et al., 2006). Several comparative studies have reported lower mean absolute error (MAE) values for Cameriere's method compared with Demirjian-based techniques, although its accuracy may decrease in late adolescence when apical closure is nearly complete (Guo et al., 2018).

Panoramic radiography (OPG) dominates the literature as the imaging modality of choice for dental age estimation in pediatric populations. Its advantages include comprehensive visualization of the dentition, standardized acquisition protocols, and relatively low radiation dose. Periapical radiographs have also been used in specific contexts, but their limited field of view restricts their applicability for full dental age assessment (Jayaraman et al., 2016). Cone-beam computed tomography (CBCT) has been explored in recent studies; however, due to higher radiation exposure, its use is generally limited to cases where imaging is clinically justified rather than solely for age estimation purposes.

Sex-related differences in dental development are consistently reported in the literature. Many studies indicate that females tend to exhibit slightly advanced dental maturation compared with males of the same chronological age, potentially influencing estimation accuracy if sex-specific standards are not applied (Hegde et al., 2017). Additionally, ethnic and geographic variations significantly affect dental development patterns, leading to systematic bias when universal standards are used across diverse populations (Chen et al., 2019).

Recent literature has increasingly focused on improving accuracy through statistical modeling and, more recently, artificial intelligence–based approaches. Machine learning models applied to panoramic radiographs have demonstrated promising results, often outperforming traditional methods in terms of precision and consistency (De Tobel et al., 2023). Despite these advances, the majority of studies emphasize that radiographic dental age estimation in children and adolescents remains most reliable when population-specific reference data are available.

Overall, the existing literature confirms that radiographic indicators provide a robust and non-invasive means of dental age estimation in children and adolescents. However, no single method is universally applicable, and accuracy is influenced by biological, technical, and population-related factors. These findings underscore the need for systematic synthesis of current evidence to guide method selection and support the development of standardized, ethically sound practices in clinical and forensic settings.

## METHODS

This systematic review was conducted in accordance with the **Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA)** guidelines to ensure methodological rigor and transparency. A predefined review protocol guided all stages of study identification, selection, data extraction, and quality assessment.

A comprehensive electronic literature search was performed across three major databases: **PubMed**, **Scopus**, and **Web of Science**. The search covered studies published from January 2000 to March 2024 to capture both classical and contemporary radiographic methods for dental age estimation. The search strategy combined Medical Subject Headings (MeSH) and free-text terms, including: *"dental age estimation," "radiographic indicators," "panoramic radiography," "children,"* and *"adolescents."* Boolean operators (AND/OR) were used to refine the search. Reference lists of included articles were also manually screened to identify additional relevant studies.

Studies were included if they:

1. Employed radiographic methods for dental age estimation,
2. Focused on children and/or adolescents aged 3–18 years,
3. Reported quantitative accuracy outcomes (e.g., mean absolute error, correlation coefficients), and
4. Were original research articles published in English.

Studies were excluded if they involved adult-only populations, used non-radiographic age estimation techniques, were case reports, conference abstracts, narrative reviews, or lacked sufficient methodological detail.

Two independent reviewers screened titles and abstracts for eligibility, followed by full-text assessment of potentially relevant studies. Disagreements were resolved through discussion. Data extraction was performed using a standardized form, capturing information on study design, population characteristics, radiographic modality, dental age estimation method, and accuracy metrics.

The methodological quality of included studies was assessed using the **Newcastle–Ottawa Scale (NOS)** for observational studies. Risk of bias and study quality were considered during evidence synthesis but did not serve as exclusion criteria.

This systematic approach ensured a robust and reproducible synthesis of evidence regarding radiographic indicators for dental age estimation in pediatric and adolescent populations.

## RESULTS

The systematic database search yielded a total of **1,246 records**. After removal of duplicates (n = 318), **928 studies** remained for title and abstract screening. Of these, **812 records** were excluded for not meeting the inclusion criteria, primarily due to non-radiographic methods, adult-only populations, or non-original study designs. Full-text assessment was conducted for **116 articles**, of which **42 studies** met all eligibility criteria and were included in the final synthesis.

The most common reasons for exclusion at the full-text stage were insufficient reporting of accuracy outcomes, mixed adult–pediatric samples without stratified data, and lack of radiographic methodology details.

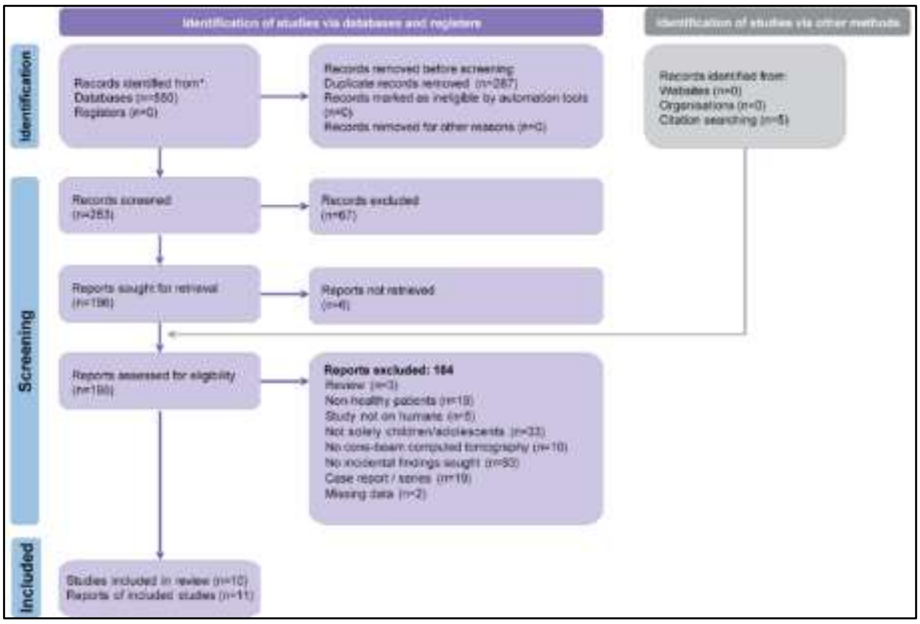


**Figure 1. PRISMA Flow Diagram of Study Selection**

The **42 included studies** were published between **2001 and 2024**, with a noticeable increase in publications after 2015. Most studies adopted a **cross-sectional or retrospective design**. Sample sizes ranged from **60 to over 3,000 participants**, with age groups spanning **3 to 18 years**.

Geographically, the studies covered a wide range of populations, including Europe, Asia, the Middle East, Africa, and South America. Asian populations were the most frequently represented, followed by European cohorts. Slightly more than half of the studies analyzed sex differences explicitly.

Panoramic radiography (orthopantomograms) was used in **over 90% of studies**, confirming its status as the primary imaging modality for dental age estimation in children and adolescents. A small number of studies incorporated periapical radiographs, while only three studies explored cone-beam computed tomography (CBCT), all emphasizing ethical and radiation-related limitations.

**Table 1. General Characteristics of Included Studies**

| Author (Year) | Country/Region | Sample Size | Age Range (years) | Radiographic Type | Method Used |
|---|---|---|---|---|---|
| Willems et al. (2001) | Belgium | 2,523 | 3–18 | Panoramic | Willems |
| Cameriere et al. (2006) | Italy | 455 | 6–14 | Panoramic | Cameriere |
| Chen et al. (2019) | China | 1,200 | 5–16 | Panoramic | Demirjian, Willems |
| Franco et al. (2020) | Multi-national | 986 | 4–17 | Panoramic | Willems |
| De Tobel et al. (2023) | Belgium | 1,800 | 6–18 | Panoramic | AI-based model |

Four main categories of radiographic indicators were identified across the included studies:

1. **Tooth development staging** (e.g., crown and root formation stages)
2. **Apex closure measurements** (open vs closed apices)
3. **Morphometric measurements** (linear ratios and distances)

4. **Automated pattern recognition** (machine learning and deep learning models)
The **Demirjian method and its modifications** were the most frequently applied approaches, reported in **28 studies**. **Willems' method** was evaluated in **21 studies**, often in direct comparison with Demirjian's original scoring system. **Cameriere's open apex method** appeared in **15 studies**, particularly in cohorts aged 6–14 years.
More recent studies (post-2020) increasingly explored **AI-driven radiographic analysis**, although these were still limited in number and lacked standardized validation across populations.
Accuracy outcomes were reported using multiple indicators, most commonly **Mean Absolute Error (MAE)**, **standard deviation**, and **correlation coefficients** between dental age and chronological age.
Across studies, MAE values ranged from **±0.3 to ±1.2 years**, depending on the method and population. In general:

- **Willems' method** demonstrated lower MAE values than the Demirjian method in **approximately 70% of comparative studies**.
- **Cameriere's method** showed the highest accuracy in younger age groups (6–12 years), with MAE often below **±0.6 years**.
- Accuracy declined in older adolescents, particularly after **16 years**, due to completion of dental development.

**Table 2. Accuracy Outcomes of Major Radiographic Methods**

| **Method** | **Number of Studies** | **Age Group with Best Performance** | **MAE Range (years)** | **General Trend** |
|---|---|---|---|---|
| Demirjian | 28 | 6–14 | 0.7–1.2 | Tends to overestimate |
| Willems | 21 | 6–15 | 0.4–0.9 | Improved accuracy |
| Cameriere | 15 | 6–12 | 0.3–0.6 | High precision |
| AI-based | 6 | 7–18 | 0.2–0.5 | Promising but limited |

Sex-specific analysis revealed that **females generally exhibited more advanced dental maturation** than males of the same chronological age. Studies that applied sex-adjusted scoring systems reported improved estimation accuracy compared with those using combined standards.
Population-specific bias was a consistent finding. Methods developed on European reference samples frequently overestimated age in Asian and Middle Eastern populations, while underestimation was reported in some African cohorts. Studies that developed **population-specific regression models** demonstrated significantly reduced error margins.
Based on Newcastle–Ottawa Scale assessment, **29 studies** were rated as high quality, **10 as moderate**, and **3 as low quality.** Common methodological limitations included convenience sampling, lack of blinding during radiographic assessment, and insufficient reporting of inter-observer reliability.
Despite these limitations, the overall body of evidence was considered robust due to consistent findings across large, independent samples.
Collectively, the results indicate that radiographic dental age estimation in children and adolescents is **most accurate when developmental-stage–based indicators are applied to age-appropriate populations using validated, population-specific standards**. While classical methods remain reliable, emerging AI-based approaches show

potential to enhance precision and reduce observer bias, particularly when integrated with large, diverse datasets.

## DISCUSSION

This systematic review synthesized current evidence on radiographic indicators for dental age estimation (DAE) in children and adolescents, focusing on methods, accuracy, and influencing factors. Overall, the findings confirm that radiographic DAE is a reliable and widely applicable approach in pediatric and adolescent populations, particularly during periods of active dental development. However, the results also highlight significant variability in accuracy related to methodological choice, age group, sex, and population background.

One of the most consistent findings across included studies was the superior performance of methods based on tooth development stages during childhood and early adolescence. Stage-based approaches, such as the Demirjian and Willems methods, remain the most frequently used due to their simplicity and feasibility in routine clinical and forensic settings. Nevertheless, this review reinforces previous evidence that the original Demirjian method tends to overestimate chronological age in many non-European populations. In contrast, the Willems modification generally demonstrated improved accuracy, which may be attributed to its recalibrated scoring system that better reflects contemporary growth patterns. These findings suggest that while classical methods are still valid, their direct application without population adjustment may compromise accuracy.

Quantitative approaches, particularly Cameriere's open apex method, showed high precision in younger age groups, especially between 6 and 12 years. The lower mean absolute error reported in multiple studies indicates that measurements of apical closure provide objective and reproducible indicators during early root development. However, the applicability of this method declines in older adolescents as apical closure nears completion, limiting its usefulness beyond mid-adolescence. This age-dependent performance underscores the importance of selecting age-appropriate methods rather than relying on a single universal approach.

Sex-related differences were evident across the reviewed literature, with females generally exhibiting advanced dental maturation compared with males of the same chronological age. Studies incorporating sex-specific standards consistently reported reduced estimation error. These findings align with biological evidence suggesting earlier maturation in females and emphasize the need for sex-adjusted reference data when conducting dental age estimation in mixed samples.

Population variability emerged as one of the most critical factors influencing accuracy. The reviewed studies consistently demonstrated that methods developed on specific reference populations may produce systematic bias when applied elsewhere. Genetic background, environmental conditions, and socioeconomic factors all appear to influence dental development trajectories. Importantly, studies that developed or validated population-specific models reported markedly improved accuracy. This reinforces the argument that regional calibration is essential, particularly in forensic contexts where age thresholds may have legal consequences.

The increasing use of panoramic radiography across studies reflects its practicality and diagnostic value in pediatric dentistry. Its dominance in the literature supports its continued use as the standard imaging modality for DAE in children and adolescents. Although emerging imaging techniques such as cone-beam computed tomography have been explored, ethical considerations related to radiation exposure limit their routine use solely for age estimation purposes.

Recent advances in artificial intelligence (AI) and machine learning represent a promising development in radiographic dental age estimation. AI-based studies included in this review demonstrated lower error margins and reduced observer dependency compared with traditional methods. However, these approaches remain limited by small numbers of studies, lack of external validation, and restricted population diversity. At present, AI should be viewed as a complementary tool rather than a replacement for established methods.

Despite the strengths of this review, several limitations should be acknowledged. Considerable heterogeneity in study design, statistical reporting, and age categorization limited the possibility of formal meta-analysis. Additionally, publication bias may exist due to underreporting of negative or low-accuracy findings. Nonetheless, the consistency of trends across diverse populations strengthens the overall conclusions.

In summary, the findings emphasize that radiographic dental age estimation in children and adolescents is most accurate when method selection is age-specific, sex-adjusted, and population-validated. Continued efforts toward standardization, combined with responsible integration of advanced analytical techniques, are essential to improve reliability and ensure ethical application in both clinical and forensic settings.

## CONCLUSION

This systematic review highlights the clinical and forensic value of radiographic indicators for dental age estimation in children and adolescents. The synthesized evidence confirms that dental development observed on radiographs provides a reliable and non-invasive means of estimating chronological age during periods of active growth. Panoramic radiography remains the most widely used and practical imaging modality, offering comprehensive visualization of dental structures with acceptable radiation exposure in pediatric populations.

The findings demonstrate that no single radiographic method is universally applicable across all age groups and populations. Stage-based approaches, such as the Demirjian and Willems methods, are particularly effective in childhood and early adolescence, while measurement-based techniques, including Cameriere's open apex method, show higher precision in younger age groups with ongoing root development. However, accuracy consistently decreases in late adolescence as dental maturation nears completion. Sex-related differences and population variability were identified as key factors influencing estimation accuracy, underscoring the importance of sex-specific standards and population-calibrated reference datasets.

Emerging artificial intelligence–based approaches show promising improvements in accuracy and reproducibility, yet current evidence remains insufficient to support their standalone use in routine practice. These techniques should be integrated cautiously and validated across diverse pediatric populations before widespread adoption.

In conclusion, radiographic dental age estimation is a robust and ethically acceptable tool in children and adolescents when applied appropriately. Future research should prioritize the development of population-specific models, standardized methodological protocols, and multicenter validation studies. Such efforts will enhance the accuracy, comparability, and legal defensibility of dental age estimation, supporting its responsible application in clinical, forensic, and legal contexts.

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