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Age Estimation Using Dental Radiography: A Review

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Abstract
Dental age estimation using radiographic techniques plays a vital role in forensic science, clinical dentistry, anthropology, and legal investigations. Teeth are highly durable and follow predictable developmental patterns, making them reliable biological markers of age. Over the years, several radiographic methods such as Nolla's, Demirjian's, Moorrees-Fanning-Hunt, Willems, Cameriere's, and Kvaal's techniques have been developed, each with unique applicability across different age groups. While traditional approaches rely on evaluating tooth development or secondary dentin deposition, advanced imaging modalities like cone-beam computed tomography (CBCT), digital subtraction radiography, and orthopantomography have significantly improved accuracy and visualization. Moreover, artificial intelligence (AI) and machine learning models are revolutionizing the field, enabling automated, population-specific, and multimodal frameworks for age prediction. Despite limitations related to observer variability, population dependency, and radiation exposure, dental radiography remains a cornerstone in age estimation. Future advancements promise globally adaptable, precise, and ethically optimized models for forensic and clinical practice.

Keywords: Dental age estimation, Radiography, Chronological age, Anthropology, Orthopantomography

Introduction

Radiology serves as a vital technique for estimating an individual's age, especially in disciplines such as dentistry, forensic science, and anthropology. It provides a dependable means of identifying both living and deceased persons. Dental X-rays are especially useful because teeth are less affected by a person's environment, diet, or hormones compared to their bones, making them a more accurate way to figure out a person's age. Teeth are the most durable parts of the human body and don't change much over time. This makes them great for age estimation, especially teeth that are still developing.[3] The process of tooth development, from the first stages of calcification to the closure of the root tip, follows a predictable pattern that can be seen on X-rays. Since this development is primarily controlled by genetics, it's less influenced by external factors like nutrition or disease, making it a very consistent and accurate way to

estimate a person's age. The period between birth and death. The age that researchers are primarily concerned with is the chronological age.[1]The practice of using teeth to determine age has a long history. Chronological age refers to the actual age of an individual, calculated based on their date of birth and the date of observation or examination. It represents the exact duration of a person's life from birth to the date of assessment. The calculation is done using the simple formula: ***Chronological Age = Date of Observation – Date of Birth***

In 1837, dentist Saunders was the first to recognize the importance of teeth for forensic purposes. Shortly after the discovery of X-rays in 1895, radiology was first used in forensic science in 1896 to find bullets in a victim's skull. It wasn't until the early 1980s that dental X-rays became a standard, non-invasive way to help with age estimation. Since then, they've become a crucial part of forensic odontology.[2] Radiological age assessment typically involves two main steps. First, a professional identifies the stage of tooth development or the amount of dentin that has been deposited.[3] Second, they compare this information to established standards to determine the person's age. Professionals use various types of X-rays for this, including panoramic X-rays, cephalometric X-rays, and more advanced 3D imaging like cone-beam computed tomography (CBCT), each offering specific benefits for different age groups.[4] The introduction of digital radiology has further improved the field. Digital images can be easily enhanced and analyzed without the need for repeated radiation exposure. Newer techniques, such as measuring the pulp-to-tooth volume ratio using CBCT scans, provide even more precise age estimates for adults. In the future, the use of artificial intelligence (AI) and deep learning in dental image analysis is expected to lead to automated, highly accurate age-prediction models.[5] This article gives an overview on Age Estimation in Dental Radiography

Historical Background

Early approaches to dental age estimation were based primarily on clinical observation of tooth eruption, a practice that has been in use for more than 170 years and was once commonly applied in contexts such as child labor regulation and legal proceedings before the advent of radiographic technology. These methods relied on eruption charts and visual inspection of the dentition but were limited in precision due to significant variability caused by factors such as nutrition, general health, and environmental influences. To overcome these limitations, the field gradually shifted toward radiographic techniques, which permit the assessment of tooth mineralization, calcification, and developmental stages parameters far less influenced by external conditions and therefore more reliable for age estimation.[6] Radiographic methods not only enhanced accuracy in children but also extended applicability to adults through the evaluation of regressive changes such as secondary dentin deposition and pulp-to-tooth ratio measurements.[7] Different methods of age estimation using dental radiography include: **Demirjian's Method, Nolla's Method, Moorrees, Fanning, and Hunt Method, Willems Method, Haavikko's method**, **Cameriere's method**, **Kvaal's Method**, **Acharya method**, **London Altas Method**, **Gustafson's method.** Together, these innovations mark the transition from crude eruption-based assessments to systematic radiographic staging and measurement techniques, establishing dental age estimation as a cornerstone in forensic science, clinical dentistry, and anthropological research.[9]

Tooth Development and Mineralization Method

1. Demirjian's Method -1973

Demirjian's method is one of the most widely adopted radiographic techniques for dental age estimation,

based on the developmental assessment of seven left mandibular permanent teeth (incisors, canine, premolars, and molars). Each tooth is evaluated through eight clearly defined stages of mineralization (A–H), ranging from the initiation of crown formation to complete root apex closure, with each stage assigned a specific score that, when summed and referenced against sex-specific standards, provides an estimated dental age.[10] The method is especially useful in children and adolescents due to its simplicity, reliance on a single panoramic radiograph, and the clarity of its pictorial staging system, which makes it easy to apply and ensures strong intra- and inter-examiner reproducibility. Numerous studies have demonstrated that this approach can estimate age with high accuracy, often within six months of chronological age, and it has been adapted across populations through modifications such as the Willems calibration to account for regional and ethnic growth variations.[11] However, the method has been criticized for its tendency to overestimate age in many populations outside of its original French-Canadian reference group, highlighting the necessity of population-specific recalibration formulas, such as those developed for Indian or European cohorts. Additionally, its reliability diminishes in older adolescents since the seven mandibular teeth assessed typically complete development before the age of 16, and the exclusion of third molars further limits its application in late-teen and adult forensic cases.[12] Despite these shortcomings, Demirjian's method remains a cornerstone in pediatric forensic odontology, valued for its ease of use, reproducibility, and adaptability, provided that region-specific adjustments are made to minimize systematic errors.[13]

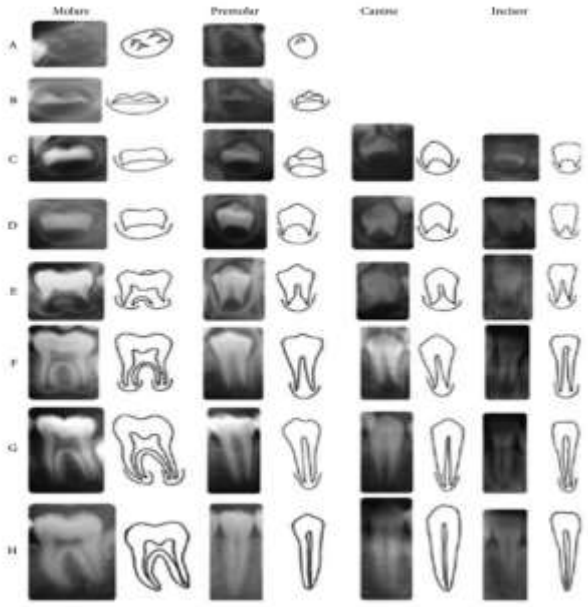


Figure-1(Demirjian's Method)

2. Nolla's Method -1960

Nolla's method is a radiographic approach to dental age estimation that categorizes each permanent tooth into one of ten developmental stages, beginning with the appearance of the crypt (Stage 1) and ending with complete root formation and apex closure (Stage 10). By scoring all teeth, typically excluding third molars, and comparing the total with gender-specific reference tables, an estimated dental age can be derived for both males and females.[14] The system has proven broadly applicable across diverse populations and is particularly effective in children between 6 and 15 years, making it valuable in clinical, forensic, and anthropological contexts for assessing dental maturity. Its strengths lie in its systematic staging,

worldwide validation, and suitability for both sexes, yet several limitations have been noted. Interpretation of radiographic stages can be subjective, leading to inter- and intra-observer variability, while ethnic and regional differences necessitate population-specific calibration to avoid under- or overestimation.[15] Furthermore, discrepancies tend to increase with age, with adolescent girls in particular often showing underestimated dental ages. The method also requires careful attention to detail, as the assignment of fractional values for intermediate stages and the summation of multiple scores can be labor-intensive and prone to error. Despite these drawbacks, Nolla's method remains a versatile and widely used tool, provided it is applied with appropriate calibration and awareness of potential observer-related variation.[16]

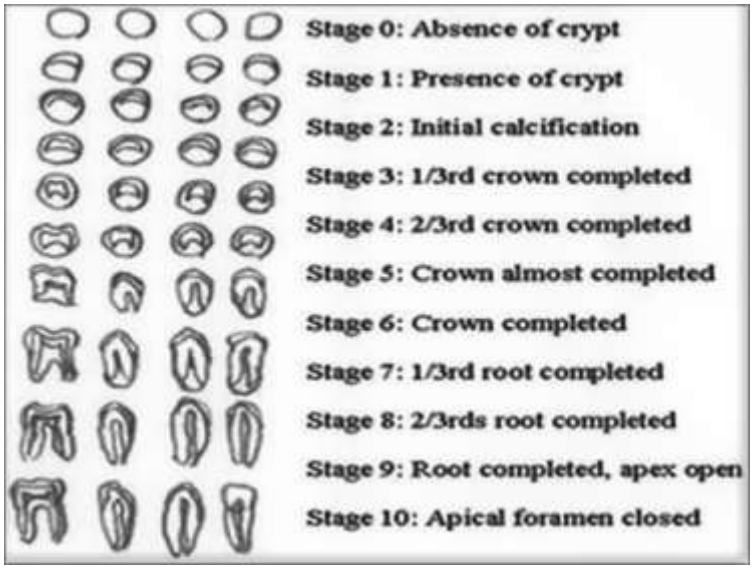


Figure-2 (Nolla's Method)

3. Moorrees, Fanning, and Hunt Method- 1965

The Moorrees, Fanning, and Hunt (MFH) method is a detailed radiographic technique for dental age estimation that employs 14 developmental stages, ranging from initial cusp formation to final root apex closure, thereby offering a much finer scale of dental maturity than earlier systems such as those of Nolla or Demirjian. It systematically evaluates crown and root mineralization across ten permanent teeth, making it broadly applicable for both children and adolescents. The strength of this method lies in its precision and granularity, as the greater number of stages enables closer alignment between dental development and chronological age, which has been confirmed through strong correlations in studies across different populations and in both sexes. Its systematic basis in tooth morphology and mineralization further enhances its scientific rigor and reliability, rendering it highly useful in pediatric dentistry, forensic odontology, and anthropological studies. However, despite these advantages, the MFH method is often regarded as complex and time-consuming, requiring significant examiner training and attention to detail for accurate stage assignment.[17] Additionally, like other methods, it is not universally calibrated, meaning population-specific differences can lead to systematic under- or overestimation unless local reference standards are developed. Moreover, its accuracy decreases in older adolescents, as dental development tends to plateau once permanent dentition is complete. Overall, the MFH method is valued for its precision and methodological robustness but must be applied with caution due to its complexity, need for expertise, and susceptibility to observer variation.[18]

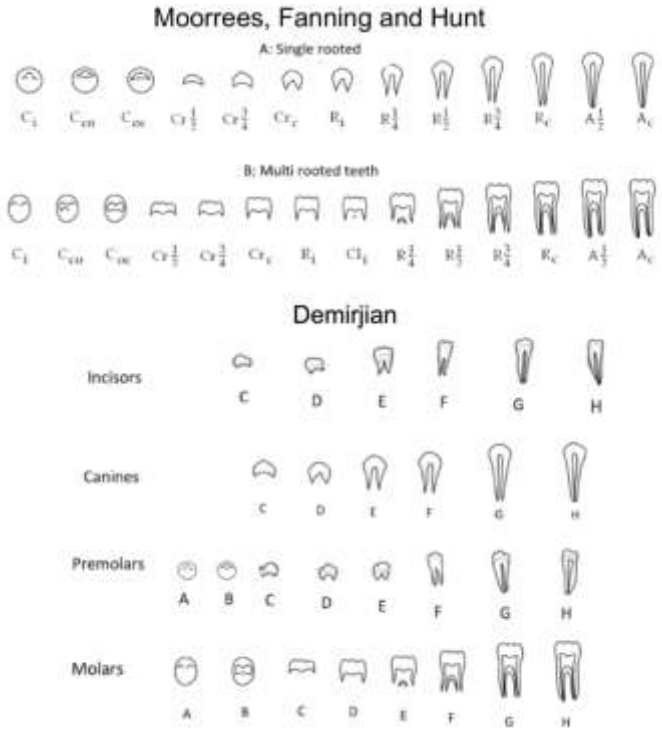


Figure-3 (Moorrees, Fanning, and Hunt Method)

4. Willems Method -2001

The Willems method is a simplified adaptation of Demirjian's dental age estimation system, in which the original stage-to-maturity score conversion was replaced by direct stage-to-age values separately calibrated for boys and girls, thereby enhancing the accuracy of chronological age prediction. Initially developed in Belgium, it has since been validated across diverse populations worldwide, consistently demonstrating better performance and reduced systematic overestimation compared to Demirjian's original approach.[19] Primarily applied to children and adolescents between 6 and 15 years of age, the Willems method has shown strong reliability in both forensic and clinical contexts. Its key strengths include higher accuracy, as it often produces estimates closer to true chronological age, along with improved reproducibility due to its straightforward scoring system that minimizes observer bias. Owing to its balance of simplicity, precision, and cross-population adaptability, the Willems method has gained widespread acceptance in pediatric dentistry and forensic odontology as a practical and refined tool for developmental age assessment.[20]

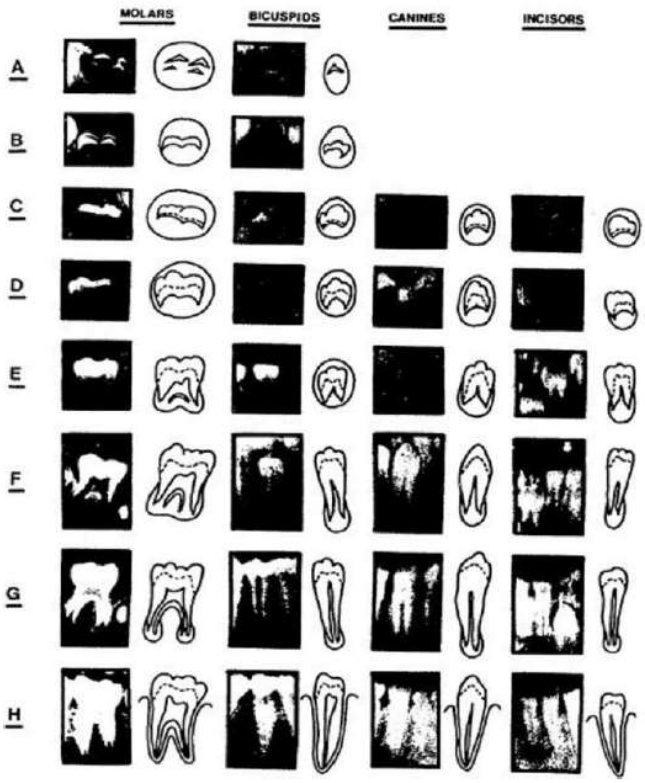


Figure 1: Original willems method, tooth developmental staging from A to H.

Figure-4(Willems Method)

5. Haavikko's method

Haavikko's method is a dental age estimation technique widely applied in children that evaluates the development of both maxillary and mandibular teeth using 12 radiographic stages, six dedicated to crown formation and six to root formation, covering the entire process from initial calcification to apex closure. Typically applied to all permanent teeth except third molars, it is most suitable for children between 2 and 13 years, although selected teeth may be assessed in older or younger groups. The developmental stages of the examined teeth are scored, averaged, and compared against standardized reference tables to estimate age. Unlike methods that focus primarily on mandibular teeth, Haavikko's approach offers the advantage of assessing both jaws, making it more versatile when teeth are missing. It is used in both clinical and forensic pediatric contexts, though like most techniques, it requires population-specific calibration as ethnic differences may lead to systematic errors, with some studies reporting a tendency toward underestimation. The method's detailed 12-stage framework allows fine granularity but also demands greater examiner expertise, introducing potential observer variability. Accuracy studies indicate that while Haavikko's method can be less precise than Willems in some populations, it may outperform Demirjian, with mean deviations from chronological age typically within 0.5–1 year depending on the cohort studied.

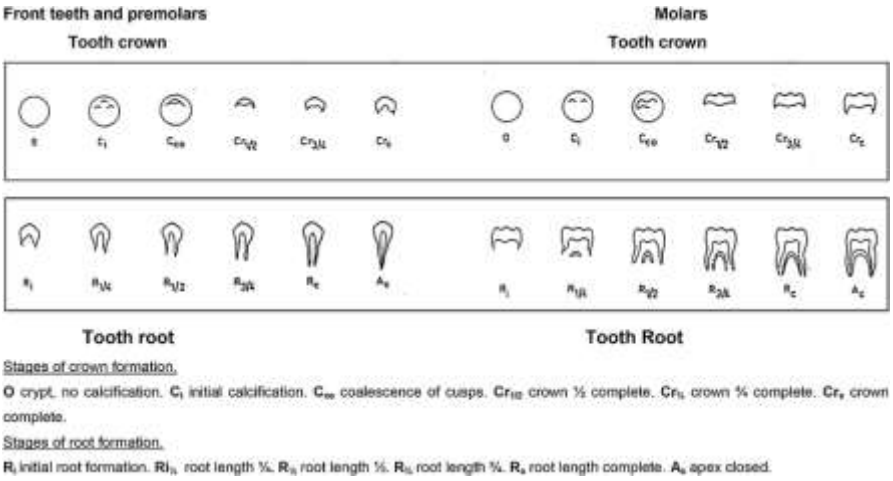


Figure-5(Haavikko's method)

Pulp -Tooth Ratio Method

6. Cameriere's method

Cameriere's method is a radiographic technique for dental age estimation that relies on measuring the pulp-to-tooth area ratio, most commonly from panoramic images. It evaluates the widths of open apices in the seven left mandibular permanent teeth and normalizes these measurements against tooth length to minimize magnification errors, with the resulting values entered into regression equations to estimate chronological age. This approach is versatile, being applicable to both children typically between 4 and 15 years through assessment of root apex closure, and to adults via analysis of age-related changes in pulp size. Its major advantages include being non-invasive, cost-effective, and relatively quick, since it only requires standard radiographs combined with simple image processing software.[21] Numerous studies have shown that regression models based on Cameriere's approach can explain up to 80–90% of age variability, often with a margin of error of less than one year, making it highly reliable in forensic contexts. Importantly, the method has been adapted across multiple populations worldwide including European, Indian, and Malaysian cohorts by incorporating gender and regional differences into specific regression formulas, thereby improving accuracy and addressing variations in dental maturation across ethnic groups. Owing to its simplicity, reliability across different age groups, and adaptability through population-specific calibration, Cameriere's method is regarded as one of the most practical and accurate tools in both forensic odontology and clinical dentistry.[22]

Figure-6(Cameriere's method)

7. Kvaal's Method

Kvaal's method is a radiographic approach for dental age estimation that relies on assessing secondary dentin deposition, which gradually reduces the pulp cavity size relative to the tooth as age advances after dental development is complete. It is particularly valuable for estimating age in adults, where growth-related markers are no longer useful. The technique typically employs periapical radiographs or panoramic radiographs (OPGs), from which linear measurements of pulp and tooth lengths and widths at specific sites are obtained and then converted into ratios to minimize magnification errors. These pulp/tooth ratios are applied to regression equations, sometimes refined for population-specific calibration, to estimate chronological age.[23] The method has proven useful for individuals aged 20 years and above, with studies reporting reasonable accuracy, often yielding standard errors between 3 and 7 years, though outcomes may vary depending on observer consistency, ethnic variations, and the quality of radiographic visualization. Factors such as restorations, pathologies, or poor imaging that obscure pulp morphology can reduce precision, yet the method remains a non-invasive, practical, and widely applied tool in forensic odontology and medico-legal contexts for quantifying age-related dental changes.[24]

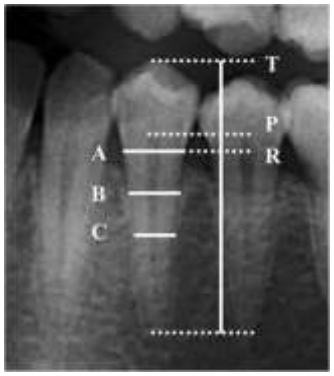
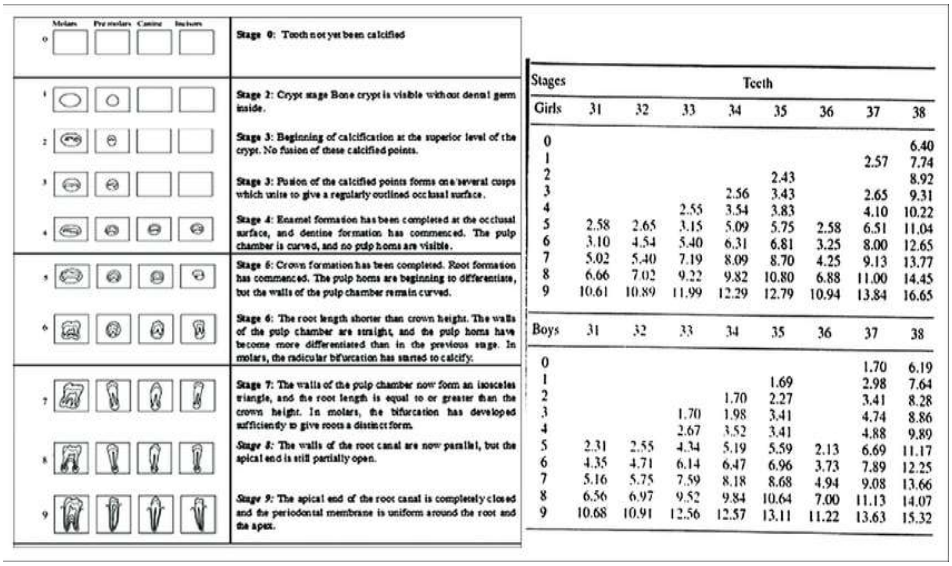


Figure-7(Kvaal's Method)

Third Molar Eruption

8. Acharya method

The Acharya method is an India-specific adaptation of Demirjian's dental age estimation technique, developed by Dr. Anil K. Acharya to address the consistent overestimation observed when applying Demirjian's original French-Canadian formulas to Indian children. This method extends the assessment to all eight teeth in the left mandibular quadrant, including the third molar, thereby broadening the applicable age range to approximately 7–23 years. By studying a large Indian sample, Acharya formulated gender-specific regression equations that correlate summed maturity scores (and their squared and cubed values) with chronological age, significantly improving accuracy for the Indian population. These equations reduce the margin of error and provide more reliable estimates compared to Demirjian's method, with alternative formulas also available for younger age groups excluding the third molar. The Acharya method has gained widespread adoption in forensic, pediatric, and orthodontic contexts in India due to its higher accuracy, though like other staging methods, it remains dependent on high-quality radiographs and careful examiner calibration. Its primary limitation is its population-specific nature, as accuracy diminishes if applied outside Indian demographics, necessitating recalibration for other ethnic groups.[25]



Stages	Teeth							
Girls	31	32	33	34	35	36	37	38
0								6.40
1							2.57	7.74
2					2.43			8.92
3				2.56	3.43		2.65	9.31
4			2.55	3.54	3.83		4.10	10.22
5	2.58	2.65	3.15	5.09	5.75	2.58	6.51	11.04
6	3.10	4.54	5.40	6.31	6.81	3.25	8.00	12.65
7	5.02	5.40	7.19	8.09	8.70	4.25	9.13	13.77
8	6.66	7.02	9.22	9.82	10.80	6.88	11.00	14.45
9	10.61	10.89	11.99	12.29	12.79	10.94	13.84	16.65
Boys	31	32	33	34	35	36	37	38
0							1.70	6.19
1					1.69		2.98	7.64
2				1.70	2.27		3.41	8.28
3			1.70	1.98	3.41		4.74	8.86
4			2.67	3.52	3.41		4.88	9.89
5	2.31	2.55	4.34	5.19	5.59	2.13	6.69	11.17
6	4.35	4.71	6.14	6.47	6.96	3.73	7.89	12.25
7	5.16	5.75	7.59	8.18	8.68	4.94	9.08	13.66
8	6.56	6.97	9.52	9.84	10.64	7.00	11.13	14.07
9	10.68	10.91	12.56	12.57	13.11	11.22	13.63	15.32

Figure-8(Acharya method)

9. London Altas Method

The London Atlas method, introduced by AlQahtani et al. in 2010, is a pictorial and chart-based system for dental age estimation that relies on high-resolution images and drawings of human teeth development from 28 weeks in utero to 23 years of age. It works through visual comparison, where examiners match a subject's dental radiographs or clinical observations with standardized atlas images that represent different developmental stages, allowing age assignment based on the closest resemblance.[26] Covering both primary and permanent dentitions, the atlas provides comprehensive age assessment across a wide range, with or without third molars depending on the age group. Originally developed from British and Bangladeshi samples, it has been validated in diverse populations worldwide, generally achieving mean errors within one year of chronological age. The method is valued for its simplicity and speed, requiring no complex measurements or calculations, making it especially practical for forensic applications such as legal investigations, adoption and asylum cases, as well as for clinical use in pediatric and orthodontic planning. It demonstrates high accuracy in children and early adolescents, though its precision declines in older teenagers and young adults due to reliance on the highly variable third molars. While calibration may be necessary for certain ethnic populations, the London Atlas has broad applicability and is now supported by interactive software developed at Queen Mary University of London, available in multiple languages to facilitate global use.[27]

Periodontin / Root Transparency Methods

10. Gustafson's method

Gustafson's method, introduced in 1950, is a classic forensic odontology technique for adult age estimation that evaluates six regressive dental changes: attrition, periodontal ligament attachment, secondary dentin deposition, cementum apposition, root resorption, and root translucency. Each parameter is scored on a scale from 0 (absent) to 3 (severe), with the sum of scores (Y) applied to a regression formula (Age = 11.43 + 4.56 × Y) to estimate chronological age. Initially, the method demonstrated an average error of about 3.6 years, though later studies, especially in populations such as Indian cohorts, have shown wider errors ranging from 5–8 years. It is primarily applied in forensic contexts for adult identification, particularly when only teeth are available, such as in cases involving fire or decomposition where skeletal

markers are unreliable. Despite its usefulness, the method has significant limitations, including its invasive and destructive nature requiring extracted or sectioned teeth, as well as subjective scoring that introduces observer variability. External influences like diet, disease, and environmental conditions may further affect the regressive changes, impacting accuracy. Nevertheless, accuracy improves when multiple teeth are assessed, and various modifications over time, such as refined scoring systems and updated regression models, have been developed to minimize subjectivity and enhance reliability.[28]

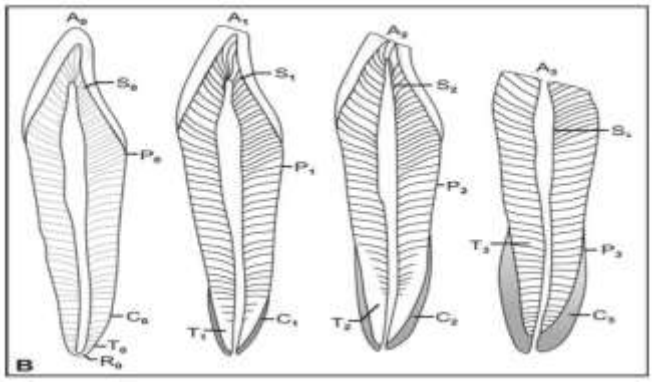


Figure-9(Gustafson's method) Age changes in teeth, Gustafson G (1958)

A–Attrition S–Secondary dentine deposition
P–Apical migration of periodontal ligament membrane
T–Root transiucency
C–Cementum deposition
R–Root apical closure
Source: Karjodkar FR. *Textbook of Dental and Maxillofacial Radiology.* 2nd ed. Mumbai: Jaypee Brothers Medical Publishers; 2013.

Advanced Techniques

Recent advances in dental age estimation have expanded precision and applicability beyond conventional 2D radiographs by incorporating modern imaging and analytical techniques. Cone Beam Computed Tomography (CBCT) allows three-dimensional visualization of teeth and surrounding structures, offering volumetric accuracy in assessing root development, pulp chamber morphology, and third molar mineralization, with the advantage of eliminating distortion seen in 2D imaging, though its higher radiation dose, cost, and limited availability restrict routine application. Digital subtraction radiography, by comparing serial radiographs and subtracting overlapping structures, enhances detection of subtle pulp chamber changes and secondary dentin formation, making it useful for longitudinal monitoring, although it is constrained by the need for high-quality sequential images. Orthopantomography (OPG), or panoramic radiography, continues to be the most widely used technique for forensic and clinical purposes due to its accessibility, comprehensive dentition coverage, and low radiation exposure, with recent integration of automated image analysis and AI significantly improving accuracy (often within ± one year) while reducing observer bias and expediting assessment. Collectively, these advanced modalities enhance the objectivity, precision, and clinical utility of dental age estimation, despite challenges related to radiation exposure, cost, and technical demands.[29]

Future Perspectives

Future perspectives in dental age estimation are increasingly focused on harnessing advanced technologies such as artificial intelligence (AI), machine learning, and multimodal approaches to overcome the limitations of traditional methods and enhance accuracy. AI-driven models, including systems like DeepTooth, have demonstrated significant improvements in predictive precision by reducing manual error and achieving lower root mean square error (RMSE) values, thereby streamlining the estimation process and making it faster and more objective . Hybrid architectures, such as the HCNN-KNN model, which combines convolutional neural networks with K-nearest neighbors, have further advanced precision, with reported accuracies reaching estimations within a few months of actual chronological age. The integration of cone beam computed tomography (CBCT) with deep learning algorithms allows volumetric analysis of teeth and surrounding structures, providing detailed three-dimensional data on root development, pulp chamber volume, and third molar mineralization with unprecedented accuracy.[29] Furthermore, there is a growing emphasis on developing population-specific AI models that account for regional and ethnic variations in dental development, thereby minimizing systemic errors common in universal models. Another promising direction is the combination of dental radiography with other biomarkers, such as skeletal or biochemical indicators, to create multimodal frameworks that enhance reliability across age groups, especially in mixed dentition and adulthood where single-method accuracy declines. Collectively, these advancements indicate that the future of dental age estimation will be defined by automated, AI-powered, and multimodal systems that offer higher precision, population adaptability, and broader clinical, forensic, and anthropological applicability.[30]

Comparative Summary

Method	Age Group	Radiograph Type	Key Features	Advantages	Limitations
Demirjian's Method (1973)	3–16 years	Panoramic (OPG)	7 left mandibular teeth staged A–H; maturity scores converted to age	Simple, reproducible, widely validated, high accuracy in children	Overestimates in non-French-Canadian populations; limited after 16 yrs; excludes 3rd molars
Nolla's Method (1960)	6–15 years	Periapical / OPG	10 stages (crypt to apex closure) for all permanent teeth (except 3rd molars)	Applicable to both sexes, systematic staging, globally validated	Observer variability; population calibration needed; underestimation in adolescent girls; labor-intensive
Moorrees, Fanning &	3–16 years	Periapical / OPG	14 stages from cusp formation to	High precision and	Complex, time-consuming, needs

Method	Age Group	Radiograph Type	Key Features	Advantages	Limitations
Hunt (1965)			apex closure; 10 permanent teeth assessed	granularity; strong correlation with chronological age	expertise; accuracy declines after full dentition
Willems Method (2001)	6–15 years	Panoramic (OPG)	Simplified Demirjian with direct stage-to-age values calibrated by sex	Higher accuracy than Demirjian; less overestimation; reproducible	Restricted mainly to children; population calibration still required
Haavikko's Method	2–13 years	Periapical / OPG	12 stages (6 crown, 6 root) for maxillary & mandibular teeth (excl. 3rd molars)	Broader tooth coverage; useful when teeth are missing; clinical + forensic	Population specific; tendency to underestimate; requires trained examiners
Cameriere's Method (Pulp-Tooth Ratio)	4–15 yrs (apex), adults (pulp size)	Panoramic (OPG)	Measures open apices and pulp/tooth ratios; regression models	Non-invasive, cost-effective, explains up to 80–90% variability	Needs population formulas; image quality dependent
Kvaal's Method	Adults (20+ years)	Periapical / OPG	Uses pulp/tooth ratios to assess secondary dentin deposition	Practical, non-invasive, useful for adults	Moderate accuracy (3–7 yrs error); affected by restorations, pathology, imaging
Acharya's Method (India-specific)	7–23 years	Panoramic (OPG)	Adapted from Demirjian; includes 8 mandibular teeth with 3rd molar; regression equations for Indian population	Higher accuracy in Indian cohorts; broader age range	Population-specific; not valid outside Indian samples; examiner calibration needed
London Atlas	28 weeks IU – 23 yrs	Clinical / Radiographic	Visual comparison with atlas images	Simple, fast, mean error <1	Accuracy drops in late teens; needs

Method	Age Group	Radiograph Type	Key Features	Advantages	Limitations
Method (2010)			of tooth development	year; global applicability; covers primary & permanent dentition	calibration for ethnicity; 3rd molar variability
Gustafson's Method (1950)	Adults (20+ years)	Extracted/Sectioned teeth (microscopic)	Evaluates 6 regressive changes (attrition, PDL, secondary dentin, cementum, resorption, translucency)	Classic adult age method; average error 3–5 yrs; useful when only teeth remain	Invasive, destructive; subjective scoring; influenced by external factors
Advanced Imaging (CBCT, Digital Subtraction, OPG + AI)	All ages (depending on application)	CBCT, OPG, Serial Radiographs	3D volumetric analysis (CBCT), pulp changes (digital subtraction), AI-based automated OPG analysis	Higher accuracy (±1 year); reduces observer bias; objective, automated	Higher cost, radiation dose, limited access, requires technical expertise

Applications

Dental age estimation serves as a vital tool across multiple disciplines including forensic, clinical, legal, and anthropological contexts due to the durability and predictable development of teeth. In forensic dentistry, it plays a central role in identifying unknown individuals, particularly in mass disasters or cases where other identification methods are not viable, and is also applied in age estimation of both the living and deceased for narrowing identification possibilities or addressing legal age disputes. Within pediatric dentistry, it is valuable for assessing dental maturity, planning orthodontic treatments, timing interventions such as braces or extractions, and monitoring overall growth and development. Legally and in medicolegal investigations, it supports establishing age in situations involving criminal responsibility of minors, immigration or adoption cases, and verification in sensitive matters such as child labor, trafficking, and sexual abuse.[31] In anthropological and archaeological research, dental age estimation assists in reconstructing demographic profiles of past populations, exploring health and life expectancy patterns, and understanding population structures. Collectively, its applications make dental age estimation a reliable and widely accepted indicator of biological age, bridging clinical care, forensic science, law, and research.[32]

Limitations

Dental age estimation methods face several limitations that affect their accuracy and ethical application. One of the major challenges is their population dependency, as formulas developed for specific groups often yield variable results when applied elsewhere, leading to systematic over- or underestimation unless

recalibrated for local populations. Staging-based techniques such as Demirjian's and Nolla's are further limited by observer bias, since subjective interpretation of developmental stages can introduce intra- and inter-observer variability, emphasizing the need for training and standardization.[33] Ethical concerns also arise from the use of radiographs, as ionizing radiation poses risks particularly in children making justification, dose minimization, and consideration of safer alternatives essential. Additionally, these methods show restricted applicability in certain age groups: they are less effective in adults where development is complete and secondary factors like dentin deposition, restorations, or pathology alter accuracy, and in mixed dentition stages where careful method selection is required.[34] These constraints underscore the importance of validating methods for specific populations, adopting standardized observer protocols, minimizing radiation exposure, and integrating complementary approaches to enhance reliability and ethical use of dental age estimation. While technological advancements have significantly improved age estimation accuracy, challenges remain. Manual methods are still prevalent and can be time-consuming and error-prone. Additionally, the accuracy of AI models can vary based on the dataset and demographic factors, necessitating continuous refinement and validation across diverse populations.[35,36]

Conclusion

In conclusion, dental radiographic methods continue to serve as a cornerstone for age estimation, with each technique offering specific strengths across different age groups and applications. While traditional approaches provide reliable frameworks, emerging technologies such as advanced imaging and AI promise greater standardization, accuracy, and adaptability, paving the way toward more universally applicable models in forensic, clinical, and research contexts.

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