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Dental Age Estimation in Forensic Medicine: A Comprehensive Review of Methods and Recent AI Developments

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ABSTRACT:

Age estimation remains a cornerstone in forensic science, paediatric dentistry, and legal investigations, with dental development serving as a reliable biological indicator. Conventional approaches—such as Demirjian's, Willems', and Cameriere's methods—rely on visual assessment of dental radiographs but are often time-consuming and subject to observer variability. Recent advances in artificial intelligence, particularly deep learning using convolutional neural networks (CNNs), have automated and enhanced age estimation by analysing panoramic dental images with high precision. These AI-driven models demonstrate remarkable accuracy, in some cases achieving mean absolute errors of less than one year, and can identify developmental stages of dental germs at a level comparable to expert clinicians. Advanced frameworks, such as 3D CNNs applied to cone-beam computed tomography (CBCT), provide volumetric insights into root and pulp development, thereby improving predictive performance. Innovations such as multi-task learning, temporal modelling, and advanced feature extraction have strengthened reproducibility and scalability while explainability techniques like Grad-CAM enhance transparency and support forensic defensibility. This review underscores AI-driven dental age estimation as a promising alternative to traditional methods, offering automation, enhanced accuracy, interpretability, and potential for regulatory acceptance. A wide range of articles and books were reviewed to assess current practices and emerging trends in dental age estimation.

1. Introduction

Age estimation using dental development is a scientific method employed to determine an individual's chronological age based on the growth and maturation stages of teeth. This technique is widely applied in forensic science, anthropology, paediatric dentistry, and orthodontics, owing to the relatively stable and predictable nature of dental development compared with other biological indicators. Teeth provide a reliable index of maturation because their development is less influenced by external factors such as nutrition or hormonal changes. [1] By assessing features such as tooth formation, calcification stages, eruption timing, and root development—through clinical examination or radiographic imaging—it is possible to estimate age with

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considerable accuracy, particularly in children and adolescents. Various methodologies, including scoring systems and dental atlases, have been devised to standardise this process and improve precision across different populations. [2] Overall, dental age estimation is a crucial tool for monitoring growth, facilitating personal identification, and supporting medico-legal evaluations. A wide range of articles and books were reviewed to examine the current practices in dental age estimation.

Dental Age Estimation Methods

Dental age estimation techniques can be broadly categorised into three main groups, depending on the approach and the type of data assessed: radiological, histological (morpho-histological), and biochemical methods.[1]

- **Radiological methods**[1] are the most widely used and are non-invasive. They utilise dental X-rays or three-dimensional imaging (such as panoramic radiographs or cone-beam computed tomography [CBCT]) to evaluate tooth development and eruption.[1] Established techniques include those of Demirjian,[3] Willems,[4,7] Cameriere, Nolla,[5] London Atlas[6] and Haavikko which assess tooth mineralisation, crown and root formation, and apical closure. More recently, artificial intelligence and deep learning algorithms have been incorporated to automate image analysis, thereby enhancing efficiency and accuracy.

- **Histological methods** involve microscopic examination of extracted teeth or thin sections to identify age-related regressive features. These include enamel wear, secondary dentine formation, cementum layering, root resorption, and dentine translucency. Classic examples include Gustafson's technique and cementochronology. Such approaches are particularly useful in adult age estimation, where developmental changes have stabilised; however, they are invasive and require considerable expertise.

- **Biochemical methods** focus on chemical alterations within dental tissues, such as the racemisation of amino acids in dentine. These molecular-level techniques can provide accurate age estimates, but they are less frequently employed due to their destructive nature and the requirement for advanced laboratory facilities.

A summary of commonly used dental age estimation methods, along with their principles, age groups, advantages, and limitations, is provided in **Table 1**.

Recent Advancements

Three-Dimensional Imaging Technologies[8]
Advances in three-dimensional imaging, such as cone-beam computed tomography (CBCT), allow detailed visualisation of dental structures from multiple angles. Compared with traditional two-dimensional radiographs, CBCT provides richer information on tooth morphology, pulp chamber dimensions, and internal structures that are critical for age assessment.

Convolutional Neural Networks (CNNs)[9,10]
CNNs are a specialised form of artificial intelligence highly effective in image analysis, making them particularly well-suited to forensic odontology applications. They automatically learn complex features within dental radiographs without explicit programming for each characteristic, enabling precise identification tasks. In forensic contexts, CNNs have been applied chiefly for age estimation, sex determination, and identification using radiographs such as panoramic images. These models analyse developmental stages, root formation, and morphological cues to predict ages with accuracies often exceeding 90%. CNNs can also distinguish gender by detecting subtle dimorphic variations in tooth size and shape. Recent studies confirm that well-trained CNN models maintain high

Table 1. Various methods of dental age estimation from traditional to artificial intelligence (AI)[1,3,4,5,6,7,8,11]

Method	Principle	Age group	Basis of assessment	Advantages	Limitations
Demirjian	Staged calcification of 7	2–18 years	Panoramic radiographs	Widely tested, reproducible	May overestimate; population-

Journal of Chemical Health Risks
www.jchr.org
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	mandibular teeth				specific standards needed
Cameriere	Ratio of open root apices to tooth length	7–14 years	Radiographs	High accuracy, simple	Accuracy declines with age; not suitable for adults
Nolla	10 developmental stages (no calcification → root closure)	≤16 years	Radiographic staging of permanent teeth	Straightforward staging	Underestimation in some populations
Willems	Modified Demirjian with updated maturity scores	3–18 years	Panoramic radiographs, sex-specific tables	Better accuracy than Demirjian; validated in several populations	Slight ethnic variability
Haavikko	Crown and root mineralisation (8 stages)	6–16 years	Tooth eruption and calcification	Simple, reproducible	Limited beyond adolescence
London Atlas	Visual atlas of developmental stages	Prenatal–young adult	Comparison with atlas images	Broad coverage, intuitive	Less precise in adults
Gustafson	Six regressive changes (e.g. dentine, cementum)	Adults	Histological sections of extracted teeth	Useful when developmental data absent	Invasive; subjective scoring
Cementochronology	Counting incremental cementum layers	Adults	Microscopic root cementum	High precision in adults	Invasive, technique-sensitive
Amino acid racemisation	Chemical racemisation in dentine	Adults	Biochemical assay	Accurate in older adults	Destructive; lab-dependent
Secondary dentine thickness	Measurement of dentine deposition	Adults	Radiographs or histology	Non-invasive with imaging	High variability; low precision
Smith	Detailed calcification staging	Children/adolescents	Morphological criteria	High sensitivity in early development	Complex; examiner dependent
Pulp/tooth ratio (AI)	AI estimates pulp chamber	Children & adults	Panoramic/CBCT imaging	Non-invasive; broad age range	Still emerging; limited validation

Journal of Chemical Health Risks
www.jchr.org
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	size relative to tooth				
Buccal alveolar bone (AI)	AI measures alveolar bone height	5–15 years	Panoramic radiographs	Fast, automated	Requires high-quality imaging
AI deep learning (radiological)	Neural networks analyse OPG/CBCT	All ages with developing dentition	Automated extraction of developmental features	Eliminates observer bias, high accuracy	Data- and image-quality dependent

Abbreviations: OPG – orthopantomogram; CBCT – cone-beam computed tomography; AI – artificial intelligence.

reliability with reduced overfitting, highlighting their potential for real-world forensic use. However, robust datasets and rigorous validation remain essential to ensure admissibility in judicial settings.

Deep Learning and Artificial Intelligence (AI)[11]
The integration of deep learning models has transformed the analysis of dental images by enabling automated recognition of tooth development stages and morphological changes with high precision. These AI frameworks can process large datasets rapidly, detect complex patterns beyond human capability, and thus facilitate more reliable age estimation, particularly in challenging or borderline cases.

Recent Surveys and Meta-Analyses (2025)[11]
A recent systematic survey and meta-analysis (2025) examined deep learning applications for age estimation using panoramic radiographs, incorporating 42 studies. The review reported a pooled mean absolute error (MAE) of approximately 1.75 years, demonstrating considerable accuracy. While variability existed across studies due to methodological differences, the analysis reinforced deep learning's potential to enhance traditional approaches by automating feature extraction, reducing observer bias, and enabling large-scale analyses.

Another notable 2025 study introduced "FaceAge",[12] a deep learning model that estimates biological age from facial photographs. The system demonstrated clinical utility by improving survival predictions in cancer patients, where accelerated biological age correlated with poorer prognosis. This illustrates AI's broader applicability beyond forensic and dental contexts, extending into general healthcare and biological ageing research.

Further investigations have also emphasised improving explainability in deep learning frameworks for age and gender estimation from CBCT scans. These studies aim not only to maximise accuracy but also to enhance interpretability, which is essential for medical and forensic defensibility.

Overall Impact
These surveys and applications highlight both the rising accuracy of AI-driven age estimation and its expanding scope, spanning forensic science, clinical practice, and personalised healthcare. Technological advancements are making dental age estimation faster, more objective, and increasingly accurate. Current research underscores the need for continuous refinement of AI algorithms, expansion of comprehensive dental image databases, and integration of multimodal inputs—such as orthopantomograms (OPGs), CBCT scans, facial images, sequential imaging, and even biochemical and genetic markers—to advance the science of age estimation.[13]

. Legal and Judicial Factors Affecting AI and Advanced Forensic Odontology in Age Estimation[14,15,16,17]

1. **Evidentiary Standards and Validation** Courts require forensic methods, including AI-driven odontology age estimation, to demonstrate robust scientific grounding and reproducibility. Evidence must comply with legal standards such as the *Frye* or *Daubert* tests, which assess whether a technique is generally accepted within the scientific community, has known error rates, and is supported by peer-reviewed protocols. AI models must therefore undergo rigorous

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validation studies before their outputs can be admitted as credible evidence.

2. **Transparency and Interpretability** The opaque or “black box” nature of many AI algorithms presents challenges in courtroom settings, where opposing counsel may question the validity of findings. Judges frequently demand transparent methodologies that can be explained in clear, comprehensible terms. Consequently, forensic odontology AI tools must be supported by detailed documentation describing their design, training datasets, and levels of confidence to withstand legal scrutiny.

3. **Chain of Custody and Data Integrity** AI-assisted forensic age estimations rely on digital radiographs or dental imaging data. Courts place emphasis on maintaining strict chain of custody protocols and ensuring data integrity, so that both images and AI outputs remain unaltered and authentic. Proper handling, encryption, and authentication of digital evidence are essential to uphold its admissibility.

4. **Privacy and Ethical Compliance** Advanced forensic odontology involves processing sensitive personal health information. Legal frameworks mandate that the collection, storage, and use of such data comply with privacy and ethical standards. Regulations such as the GDPR, HIPAA, or equivalent regional laws must be observed when applying AI systems to dental records for age estimation.

5. **Standardisation and Accreditation of Forensic Laboratories** Judicial acceptance is often contingent on whether the forensic laboratory performing AI-assisted odontology is accredited and adheres to standardised protocols. Accreditation by recognised bodies assures courts of quality control and consistent practice, reducing disputes regarding evidentiary reliability.

6. **Impact on Rights and Legal Outcomes** Age estimation directly influences legal determinations such as immigration eligibility, criminal responsibility, or access to social services. As such, both accuracy and fairness are legally critical. Courts carefully evaluate AI-derived age evidence to prevent unjust outcomes, highlighting the importance of recognising system limitations and avoiding over-reliance on automated decisions.

7. **Emerging Laws and Guidelines** Governments and judicial institutions are increasingly formulating specific statutes and guidelines to regulate AI in forensic practice. These initiatives aim to ensure that AI-driven odontology evolves with safeguards for due process, transparency, and fairness in judicial proceedings.

8. **Case acceptance context**

   AI-based forensic evidence has yet to be widely tested in courts so admissibility will depend on validation and precedents.

Conclusion

Age estimation, particularly through dental analysis, plays a pivotal role in forensic science, clinical dentistry, and legal proceedings by providing reliable insights into developmental or chronological age. Owing to their durability and predictable patterns of formation and maturation, teeth remain one of the most dependable biological indicators. Numerous established methods—including those of Demirjian, Willems, Nolla, Haavikko, Cameriere, and others—offer structured approaches for different populations and age groups, yet they remain limited by observer variability, population dependence, and time-intensive procedures.

Recent advances, such as digital imaging and artificial intelligence, are refining these methodologies, delivering higher accuracy and broader applicability. State-of-the-art techniques incorporate AI-driven image analysis, alternative biological markers, and advanced statistical modelling to enable faster, more reliable, and scalable age predictions. Current research further addresses challenges in data availability and multimodal integration through innovations like data augmentation, synthetic imaging networks (e.g., generative adversarial networks [GANs]), and multi-task learning. Explainable

Journal of Chemical Health Risks

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JCHR (2026) 16(2), 255-260 | ISSN:2251-6727

AI techniques such as Grad-CAM enhance forensic transparency and strengthen courtroom admissibility by providing visual evidence of decision-making processes.

Ongoing population-specific validation and the integration of automated tools are expected to further improve the reliability and reproducibility of age estimation. Collectively, these innovations are reshaping forensic odontology and paediatric dentistry, with strong potential for continued advancement as datasets expand and algorithms become increasingly sophisticated.

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