RESEARCH PAPER

Use of Artificial Intelligence in Forensic Odontology for Age Estimation

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ABSTRACT
Forensic Odontology has become an important branch of forensic science for establishing who someone is, whether in a criminal case, a disaster, or a legal dispute over age. Because teeth are so tough and change in predictable ways, we get older, dental age estimation has become one of our most reliable tools especially when tissues are decomposed. Among the available identification techniques, dental age estimation is considered highly dependable because dental tissues are resistant to decomposition and exhibit progressive developmental and age-associated changes throughout life. Traditional methods of dental age estimation mainly rely on radiographic interpretation and morphological examination; however, these approaches are often influenced by examiner experience, subjective interpretation, and population variability. Lately Artificial Intelligence has really started to change the game in forensic dentistry, helping us analyze dental images faster and more accurately than we used to. Combining AI with modern dental imaging has led to the development of more automated and standardized methods for dental age estimation. Machine learning and deep learning algorithms, particularly Convolutional Neural Network models, have demonstrated promising performance in analyzing orthopantomograms, cone beam computed tomography images, and other dental radiographs. AI-based systems can detect subtle developmental patterns that are sometimes difficult to identify through conventional manual examination. This review examines the current applications of artificial intelligence in forensic odontology for age estimation, including commonly used AI models, imaging modalities, advantages, and limitations. In addition, the paper discusses challenges related to dataset availability, ethical considerations, algorithmic bias, and the need for population-specific validation. The review also highlights future directions and the growing role of AI-assisted technologies in enhancing the reliability and efficiency of forensic age estimation practices.

Keywords: *Forensic Odontology, Artificial Intelligence, Dental Age Estimation, Machine Learning, Deep Learning, Dental Radiography*

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INTRODUCTION
Forensic Odontology is a vital specialty that uses dental evidence to help solve legal and investigative puzzles. Teeth are incredibly resilient; they can survive fire, trauma, and extreme weather that could destroy fingerprints or facial features. Because of this, dental records are often the last hope for identifying victims in mass causalities or helping settle identity disputes.[19] Over the years, forensic odontology has contributed significantly to criminal investigations, disaster victim identification, mass casualty incidents, child abuse investigations, and civil disputes involving identity and age determination. Among the different applications of forensic odontology, age estimation remains one of the most widely studied and practically significant areas. Determining the age of an individual is essential in both living and deceased persons, especially in medico-legal situations where official documents are unavailable, forged, or disputed. Accurate age estimation is frequently required in criminal responsibility assessment, identification of unidentified bodies, adoption procedures, refugee and immigration cases, sports participation disputes, and cases involving child labor or trafficking. In many countries, legal decisions regarding punishment, consent, marriage, employment, and asylum are directly influenced by the estimated age of an individual. Consequently, the reliability and accuracy of age

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estimation methods are of considerable forensic importance. Teeth are considered reliable indicators of age since their development generally occurs in a consistent and sequential manner from childhood to adulthood. Processes such as tooth eruption, calcification, root formation, and secondary dentin deposition occur progressively with age and can be evaluated using clinical and radiographic methods. Unlike skeletal structures, teeth are less affected by nutritional deficiencies, hormonal disturbances, and environmental influences, making dental analysis comparatively more dependable. Several conventional techniques have therefore been developed for estimating age using dental characteristics. Commonly used methods include the Demirjian method, Cameriere method, Gustafson method, Nolla method, and third molar assessment techniques. [33,28] These methods are primarily based on radiographic examination and morphological evaluation of dental structures. Although traditional methods have been extensively applied in forensic practice, they possess certain limitations. Most conventional approaches depend heavily on manual observation and interpretation by experts, which may introduce subjectivity and inter-observer variability. The accuracy of these techniques may also vary across different ethnic and population groups because dental development patterns are influenced by genetic and geographical factors. In addition, manual assessment can be time-consuming, particularly when dealing with large datasets or mass disaster investigations. These limitations have encouraged researchers to explore more standardized, automated, and efficient approaches for dental age estimation. Recently the forensic world has started looking at Artificial Intelligence as a way to handle the heavy lifting of data analysis. Essentially, we are using computer systems that can see and decide like a human would – spotting patterns in dental X – rays much faster and more consistently than a manual check ever could. Within the field of dentistry, AI has already demonstrated promising applications in dental radiology, orthodontics, caries detection, implant planning, and oral pathology diagnosis. Its integration into forensic age estimation has attracted increasing attention because AI-based systems can analyze complex dental patterns with greater consistency and speed compared to traditional manual techniques. Machine learning and deep learning algorithms have particularly shown remarkable potential in analyzing dental radiographs and predicting chronological age. [34,32] AI models can be trained using large collections of dental images to recognize developmental and degenerative changes associated with aging. Techniques such as artificial neural networks, support vector machines, and models are capable of identifying subtle image features that may not be easily detectable through conventional assessment. Furthermore, AI-assisted methods may reduce examiner bias, improve reproducibility, and enhance diagnostic efficiency. The increasing availability of digital imaging systems such as orthopantomograms, cone beam computed tomography, and intraoral radiographs has further accelerated research in this area. Even with recent progress, multiple scientific and practical concerns still limit the broader use of AI in forensic dental age estimation. Issues related to limited datasets, population diversity, image quality, algorithm transparency, and ethical concerns remain significant. Many AI models are trained using population-specific data, which may reduce their applicability to individuals from different ethnic or geographical backgrounds. Additionally concerns regarding data privacy, explainability of algorithms, and legal admissibility of AI-generated conclusions require careful consideration before these systems can be fully integrated into routine forensic practice. The combination of forensic odontology and artificial intelligence has emerged as an important and rapidly developing research field with strong clinical and legal significance. Since this field is moving so fast, researchers and legal pros really need to get a handle on what AI can and can't do for dental age estimation. This review paper dives into how we currently estimate age, where AI fits in, what hurdles we still need to clear to make these tools a standard part of forensic work. [10]

BASICS OF FORENSIC ODONTOLOGY

Forensic odontology, also referred to as forensic dentistry, is a specialized branch of forensic science that involves the application of dental knowledge for legal and investigative purposes.[2] The field primarily focuses on the examination, preservation, interpretation, and presentation of dental evidence in both civil and criminal cases. Because teeth and surrounding oral structures are highly resistant to decomposition, heat, trauma, and environmental damage, they often remain preserved even when other methods of identification are no longer possible. This durability makes dental evidence an important tool in forensic investigations, particularly in cases involving decomposed, burned, fragmented, or unidentified human remains. The development of forensic odontology can be traced back several centuries, although it gained greater scientific recognition during the twentieth century with the advancement of dental radiography and forensic identification techniques. One of the earliest recorded applications of dental evidence involved the identification of individuals based on unique dental characteristics and restorations. Since then, the discipline has evolved into a well-established forensic specialty with applications in human identification, age estimation, sex determination, bite mark analysis, and disaster victim identification. Human dentition possesses several characteristics that contribute to its forensic significance. Dental structures are unique to every individual due to variations in tooth morphology, alignment, restorations, extractions, and pathological conditions. Even identical twins do not possess completely identical dentition. Dental treatments such as fillings, crowns, bridges, implants, and orthodontic procedures create additional identifying features that can assist forensic experts in establishing identity. In many cases, comparison between antemortem dental records and postmortem findings provides one of the most reliable methods of identification. One of the major applications of forensic odontology is human identification. Dental identification becomes especially valuable during mass disasters, natural calamities, terrorist attacks, aviation accidents, and situations where bodies are severely damaged.[19] In such circumstances, fingerprints and facial features may be destroyed, whereas teeth and jaw structures often remain intact. Dental records, including radiographs, treatment charts, and study models, can therefore be compared with postmortem findings to confirm identity. The role of forensic dentists in disaster victim identification has increased considerably with the occurrence of large-scale disasters worldwide. Another important component of forensic odontology is age estimation. Determining the age of an individual is frequently required in legal and medico-legal situations, especially when valid birth records are unavailable or disputed. Dental age estimation is based on the observation of developmental and degenerative changes occurring in teeth throughout life. During childhood and adolescence, age can be estimated by evaluating tooth eruption patterns, crown calcification, and root development. In adults, age assessment commonly relies on secondary dentin deposition, root transparency, attrition, and periodontal changes. Since dental development follows a relatively consistent biological pattern, teeth are considered reliable indicators of age. Sex determination is also an important area within forensic odontology. Although dental tissues alone may not provide absolute accuracy for sex estimation, certain morphological and dimensional differences between male and female dentition can assist forensic investigations. Measurements of tooth size, mandibular characteristics, and genetic analysis using dental pulp have been explored for sex determination purposes. Advances in molecular biology have further expanded the forensic value of dental tissues by enabling DNA extraction from teeth even in highly decomposed remains. Bite mark analysis represents another traditional application of forensic dentistry. [31] Bite marks may be encountered in cases involving physical assault, homicide, sexual violence, and child abuse. Forensic experts analyze the size, shape, and arrangement of bite patterns to compare them with the dentition of suspected individuals. However, the reliability of bite mark analysis has become controversial in recent years because of concerns regarding subjectivity and lack of standardization. As a result, modern forensic research increasingly emphasizes objective and technology-assisted approaches. Radiographic examination forms a fundamental aspect of forensic odontology. Dental radiographs provide valuable information regarding tooth morphology, restorations, developmental stages, and pathological conditions. Common imaging techniques used in forensic investigations include intraoral radiographs, panoramic radiography, and . These imaging modalities are particularly important in age estimation studies because they allow detailed visualization of tooth formation and internal structures. Digital imaging has further improved the efficiency, storage, and comparison of forensic dental records. Recent technological advancements have significantly influenced the practice of forensic odontology. Digital databases, computer-assisted image analysis, three-dimensional imaging, and artificial intelligence-based systems are increasingly being integrated into forensic investigations. These technologies improve the accuracy, speed, and reproducibility of forensic analyses while reducing observer-related errors. The growing use of artificial intelligence in dental radiology and age estimation demonstrates the evolving nature of forensic odontology and its adaptation to modern technological developments. Despite its importance, forensic odontology faces several challenges. Variations in dental development among populations, limited availability of dental records, ethical concerns, and differences in forensic standards across countries may affect the reliability of forensic conclusions. Additionally, some traditional methods such as bite mark analysis continue to face criticism due to concerns regarding scientific validity. Therefore, ongoing research and technological advancements remain essential for improving the accuracy and credibility of forensic dental investigations. Overall, forensic odontology serves as a vital interdisciplinary field that combines dentistry, medicine, radiology, anthropology, and legal science. Its contributions to identification and age estimation continue to play a crucial role in modern forensic practice. With the integration of emerging technologies such as artificial intelligence and digital imaging, forensic odontology is expected to become increasingly precise, objective, and efficient in the future.

FUNDAMENTALS OF AGE ESTIMATION

Age estimation is an important component of forensic science and medico-legal investigations, involving the assessment of an individual’s chronological age based on biological indicators. In forensic practice, age estimation becomes necessary when reliable birth records or identification documents are unavailable, incomplete, or suspected to be inaccurate. The determination of age plays a crucial role in both living and deceased individuals and is widely used in criminal investigations, civil disputes, immigration cases, adoption procedures, sports eligibility verification, disaster victim identification, and cases involving child labor or trafficking. Because legal rights and responsibilities are often dependent on age, accurate estimation is of considerable social, medical, and judicial significance. Age estimation works because our bodies are constantly changing. From the moment we’re born until we get old, our teeth and bones leave a biological paper trail that forensic experts can follow to pinpoint a person’s. These changes occur in skeletal structures, teeth, soft tissues, and various physiological systems. Different biological indicators are therefore used to estimate age depending on the stage of life and the condition of the individual. Among the available biological structures, teeth are considered one of the most reliable indicators because dental development follows a relatively organized and genetically controlled pattern. Furthermore, dental tissues are more resistant to environmental influences and postmortem destruction compared to many other body tissues. In forensic investigations, a distinction is commonly made between chronological age and biological age. Chronological age refers to the actual age of an individual calculated from the date of birth, whereas biological age represents the physiological and developmental status of the body. In some individuals, biological age may differ from chronological age due to factors such as genetics, nutrition, disease, hormonal imbalance, and environmental influences. Age estimation techniques therefore aim to approximate chronological age by analyzing biological characteristics associated with growth and aging. Age estimation methods are generally categorized according to different stages of life. In prenatal and neonatal periods, developmental indicators such as fetal growth and tooth germ formation are commonly assessed. During childhood and adolescence, dental and skeletal development provide highly reliable indicators because active growth processes are occurring. In adults, however, age estimation becomes more challenging because developmental changes are largely complete, and assessment depends mainly on degenerative alterations such as attrition, secondary dentin deposition, root transparency, and periodontal changes. Dental age estimation is particularly valuable because tooth formation and eruption occur in a predictable sequence. [28] The process of odontogenesis begins during fetal development and continues until the completion of third molar formation in early adulthood. Different stages of dental development, including crown formation, calcification, eruption, and root completion, can be evaluated clinically and radiographically to estimate age. These developmental stages are less affected by nutritional and endocrine disturbances than skeletal growth, making dental assessment comparatively more reliable in many situations. Several biological events contribute to dental age estimation. Tooth eruption refers to the movement of teeth into their functional position within the oral cavity. Although eruption timing can provide useful information, it may be influenced by local and systemic factors and therefore may not always accurately reflect chronological age. Calcification stages, on the other hand, are considered more dependable because mineralization follows a relatively stable developmental pattern. [7] Radiographic examination of calcification and root development has therefore become a widely accepted method for estimating age in children and adolescents. In adults, age estimation relies mainly on degenerative changes occurring within dental tissues. Secondary dentin deposition gradually reduces the size of the pulp chamber with increasing age. Similarly, attrition caused by mastication leads to progressive tooth wear, while periodontal recession and root transparency also increase over time. Histological and radiographic evaluation of these changes can provide valuable information for adult age estimation, although accuracy generally decreases with advancing age. Multiple factors can influence the accuracy of age estimation methods. Genetic background plays an important role in determining the timing of dental development and maturation. Ethnic and population-related differences have been observed in eruption patterns and calcification stages, making population-specific standards necessary for accurate assessment. Nutritional status, systemic diseases, hormonal disorders, and environmental conditions may also influence developmental timing. Therefore, age estimation methods developed for one population may not always produce equally reliable results in another population. Radiographic imaging has become a fundamental tool in modern age estimation procedures. Dental radiographs allow visualization of tooth formation, eruption status, root development, and internal structural changes. Commonly used imaging modalities include intraoral radiographs, panoramic radiographs. The introduction of digital radiography has improved image quality, storage, and analytical capabilities, enabling more accurate and reproducible assessments. Traditional methods of age estimation often rely on manual interpretation by experienced examiners, which may introduce subjectivity and observer-related variability. In recent years, the integration of into forensic age estimation has gained increasing attention. Artificial intelligence-based systems can analyze large datasets of dental images, identify complex developmental patterns, and provide automated predictions with improved consistency and efficiency. [6] Machine learning and deep learning techniques have demonstrated promising results in reducing human error and enhancing the reliability of dental age estimation. Despite considerable advancements, age estimation remains a challenging area of forensic science. No single method can provide absolute accuracy for every individual or population group. Therefore, forensic experts often combine multiple approaches to improve reliability and minimize error. Further research and large-scale validation studies are necessary to improve the reliability and standardization of forensic age estimation methods. Overall, the fundamentals of age estimation are based on the systematic evaluation of biological growth and aging processes. Among the available methods, dental analysis remains one of the most dependable approaches because of the durability and predictable developmental characteristics of teeth. The growing incorporation of advanced imaging technologies and artificial intelligence is expected to further improve the precision, objectivity, and practical application of forensic age estimation in the future.

CONVENTIONAL DENTAL AGE ESTIMATION METHODS

Dental age estimation has long been recognized as one of the most dependable approaches in forensic science because dental tissues exhibit progressive developmental and degenerative changes throughout life. Conventional dental age estimation methods are primarily based on the assessment of tooth eruption, mineralization, root formation, and age-related structural alterations observed clinically, radiographically, or histologically. These methods have been extensively applied in forensic investigations, anthropology, pediatric dentistry, and legal medicine for determining the approximate chronological age of both living and deceased individuals. The reliability of dental age estimation is largely attributed to the relatively stable and genetically controlled nature of dental development. Compared to skeletal maturation, dental formation is less affected by environmental factors such as nutrition, hormonal imbalance, and systemic diseases. Consequently, several conventional methods have been developed over the years, each utilizing specific developmental or degenerative dental parameters. These methods differ according to the age group being examined, the imaging modality used, and the biological changes being assessed.

DEMIRJIAN METHOD

One of the most widely used dental age estimation techniques is the Demirjian method, developed by in 1973. This method is based on the radiographic evaluation of the developmental stages of seven permanent mandibular teeth on the left side using panoramic radiographs. Each tooth is assigned a developmental stage from A to H according to the degree of crown and root formation. These stages are then converted into numerical scores, and the total maturity score is used to estimate dental age.[14]The Demirjian method gained widespread acceptance because of its simplicity, reproducibility, and relatively high accuracy in children and adolescents. Since it relies on calcification stages rather than eruption patterns, it is considered more reliable than eruption-based methods. However, one of the major limitations of this technique is population variability. Studies conducted in different ethnic groups have shown that the original French-Canadian standards often overestimate or underestimate age when applied to other populations. As a result, modified population-specific versions of the Demirjian method have been developed in several countries.

Nolla Method

The Nolla method is another commonly used approach for estimating dental age. This method evaluates tooth development using ten stages of calcification ranging from absence of crypt formation to complete root apex closure. Each tooth is assigned a numerical score based on its developmental stage, and the combined score is used to estimate chronological age.The Nolla method is particularly useful in pediatric and adolescent populations because it provides a detailed description of developmental progression. It is considered relatively simple and applicable to various dental radiographs. However, interpretation of intermediate stages may sometimes be subjective, resulting in observer variability. Similar to other traditional methods, the accuracy of the Nolla method may vary among different ethnic populations.

Cameriere Method

The Cameriere method, introduced by , is based on the measurement of open apices in developing teeth. This radiographic technique evaluates the degree of root development by measuring the width of open root apices relative to tooth length. Mathematical regression formulas are then applied to estimate age.[7] One of the major advantages of the Cameriere method is its quantitative nature, which reduces subjectivity associated with visual staging systems. It has demonstrated good accuracy in children and adolescents and has been validated in multiple populations. In addition, the method can be applied using digital image analysis, improving reproducibility and precision. Nevertheless, the method still requires population-specific calibration because dental maturation rates differ among ethnic groups.

Gustafson Method

The Gustafson method is primarily used for adult age estimation and is based on degenerative changes observed in dental tissues. Proposed by in 1950, this technique evaluates six age-related criteria: attrition, periodontal recession, secondary dentin deposition, cementum apposition, root resorption, and root transparency. Each parameter is scored according to its severity, and the total score is used to estimate age.[28] The Gustafson method represented a major advancement in adult dental age estimation because it incorporated multiple physiological changes associated with aging. Root transparency is generally considered the most reliable parameter among the six criteria. However, the technique requires extraction and sectioning of teeth, making it invasive and unsuitable for living individuals. Subjective interpretation of degenerative changes and variation in scoring also contribute to limitations in accuracy.

Kvaal Method

The Kvaal method is another important technique used mainly for adult age estimation. Unlike Gustafson’s method, Kvaal’s approach is non-destructive and based on radiographic measurements of the pulp chamber and tooth dimensions. Age estimation is achieved by analyzing the reduction in pulp cavity size caused by secondary dentin deposition over time. This method is advantageous because it can be performed using routine dental radiographs without the need for tooth extraction. It has therefore become increasingly popular in forensic investigations involving living individuals. However, image distortion, radiographic angulation, and anatomical variation may influence measurements and reduce accuracy.

Moorrees Method

The Moorrees method evaluates detailed stages of crown and root development for permanent teeth. This technique divides tooth formation into multiple developmental stages, allowing precise assessment of dental maturation. Because of its detailed classification system, the method provides highly accurate developmental information and is frequently used in anthropological and forensic studies. Despite its accuracy, the Moorrees method is relatively complex and time-consuming compared to simpler staging systems. Proper training and experience are often required for accurate interpretation of developmental stages.

Third Molar Assessment

Third molars, commonly known as wisdom teeth, are frequently used for age estimation in late adolescence and early adulthood because they are the last teeth to develop. Evaluation of third molar mineralization, eruption status, and root formation can assist in determining whether an individual has reached the legal age threshold of 18 years.[23] Third molar assessment is widely used in forensic and immigration cases; however, its reliability remains controversial because third molar development exhibits considerable variation among individuals and populations. Agenesis, impaction, and delayed eruption may further complicate assessment. Consequently, third molar analysis is usually combined with other methods to improve reliability.

Atlas-Based Methods

Atlas-based techniques involve comparing dental radiographs with standardized developmental atlases representing average tooth formation stages at different ages. One commonly used atlas is the Schour and Massler atlas, which illustrates chronological changes in dental development from infancy to adulthood. Atlas methods are relatively simple and easy to apply because they rely on visual comparison rather than complex calculations. They are particularly useful in clinical and forensic settings where rapid assessment is required. However, the subjective nature of visual matching may reduce reproducibility, and population differences may affect accuracy.[33]

Histological Methods

Histological age estimation methods involve microscopic examination of dental tissues to identify age-related structural changes. Parameters such as incremental lines in cementum, dentin translucency, and secondary dentin deposition are commonly analyzed. Cementum annulation, which resembles growth rings in trees, has been explored as a reliable indicator of age. Histological techniques may provide high accuracy, especially in adult individuals, but they are invasive because they require tooth extraction and sectioning. These methods are therefore mainly used in postmortem forensic investigations rather than routine clinical practice.

Introduction to AI in Dentistry

Artificial intelligence (AI) has emerged as one of the most transformative technologies in modern healthcare, significantly influencing the field of dentistry. AI refers to computer systems and algorithms capable of performing tasks that traditionally require human intelligence, including learning, reasoning, pattern recognition, decision-making, and problem-solving. In dentistry, the integration of artificial intelligence with digital imaging, computer-aided diagnostics, and clinical data analysis has introduced new possibilities for improving diagnostic accuracy, treatment planning, workflow efficiency, and patient care.[10] The rapid growth of digital dentistry has created an environment in which large amounts of clinical and radiographic data are generated routinely. Dental radiographs, intraoral scans, cone beam computed tomography images, and electronic health records provide extensive information that can be analyzed using AI-based systems. Conventional dental diagnosis often depends heavily on clinician experience and manual interpretation, which may lead to variability and subjective errors. Artificial intelligence offers a more standardized and automated approach by identifying patterns and abnormalities with high speed and consistency. The foundation of AI in dentistry is largely based on machine learning and deep learning technologies. Machine learning is a branch of artificial intelligence in which computer systems learn from data and improve their performance without being explicitly programmed for every task. These algorithms identify relationships within datasets and generate predictive models capable of making decisions or classifications. Deep learning, a more advanced subset of machine learning, uses artificial neural networks with multiple hidden layers to process complex information. Among these models, algorithms have become especially important in dental imaging because they can analyze radiographic images and detect subtle anatomical features with remarkable accuracy. Artificial intelligence has found applications in several areas of dentistry. In dental radiology, AI systems are increasingly used for the detection of dental caries, periodontal bone loss, periapical lesions, cysts, tumors, and impacted teeth. [5] Automated image analysis can assist clinicians in identifying pathological changes that might otherwise be overlooked during manual examination. AI-assisted radiographic interpretation also reduces diagnostic variability and improves clinical efficiency. In orthodontics, artificial intelligence is used for cephalometric landmark identification, treatment planning, growth prediction, and evaluation of facial symmetry. [30] Traditional cephalometric analysis requires considerable time and expertise, whereas AI-based systems can automatically detect anatomical landmarks and generate measurements within seconds. Similarly, in prosthodontics and restorative dentistry, AI contributes to digital smile design, crown fabrication, implant planning, and occlusal analysis through computer-aided design and manufacturing systems.

Applications of AI are also expanding in endodontics and periodontology. Machine learning algorithms have demonstrated effectiveness in detecting root fractures, assessing root canal morphology, and predicting endodontic treatment outcomes. In periodontology, AI models can evaluate periodontal bone loss and classify periodontal disease severity based on radiographic findings. Furthermore, AI-driven predictive analytics may help clinicians identify patients at higher risk for oral diseases and develop preventive treatment strategies. One of the most promising developments in dentistry is the integration of AI into forensic odontology. [22] Dental records and radiographic images contain highly individualized information that can be analyzed using artificial intelligence for human identification and age estimation. AI systems are capable of processing large datasets rapidly while minimizing observer bias and improving reproducibility. This has generated significant interest in the use of AI for forensic dental age estimation, particularly through automated analysis of panoramic radiographs and cone beam computed tomography images. The success of AI in dentistry is closely linked to advances in digital imaging technologies. Modern imaging modalities such as panoramic radiography, intraoral scanners, and provide high-resolution images suitable for computational analysis. The availability of large annotated datasets has further accelerated the development of AI algorithms capable of recognizing dental structures and pathological changes with increasing precision. Despite its growing applications, artificial intelligence in dentistry also presents several challenges and limitations. AI systems require large quantities of high-quality data for effective training and validation. Variations in image quality, patient demographics, and clinical protocols may affect algorithm performance. In addition, concerns regarding data privacy, ethical considerations, algorithm transparency, and medico-legal responsibility remain important issues in the clinical implementation of AI technologies. Many AI models also function as “black box” systems, where the reasoning behind a prediction may not be fully explainable to clinicians or legal authorities. Another important consideration is that artificial intelligence is intended to support rather than replace dental professionals. Although AI systems can improve efficiency and assist in diagnosis, clinical expertise and professional judgment remain essential for accurate interpretation and patient management. The combination of human expertise with AI-assisted analysis is therefore considered the most effective approach for achieving reliable clinical outcomes. Research in AI-based dentistry continues to expand rapidly, with ongoing efforts to improve algorithm accuracy, develop population-specific models, and integrate AI into routine clinical workflows. The future of dentistry is expected to involve greater use of intelligent diagnostic systems, robotic-assisted procedures, personalized treatment planning, and real-time image analysis. In forensic applications, AI may contribute significantly to faster, more objective, and more accurate methods of human identification and age estimation. Overall, artificial intelligence represents a major technological advancement in dentistry, offering improved precision, automation, and analytical capabilities across multiple dental specialties. Its increasing integration into forensic odontology has opened new opportunities for enhancing the reliability and efficiency of dental age estimation methods, making AI an important area of modern forensic research.

AI Techniques Used in Age Estimation

Forensic age estimation has taken a huge gap forward lately, thanks to better digital imaging and more powerful computers. Unlike the old manual ways of doing things, AI uses smart mathematical models to pick up on the tiny, complex changes in the teeth that signals how old someone is.AI-assisted age estimation is primarily based on machine learning and deep learning algorithms trained using large datasets of dental images and chronological age information. These systems learn relationships between dental characteristics and age by recognizing recurring patterns within the data. Once trained, the algorithms can predict the approximate age of unknown individuals using newly provided radiographic or clinical images. Different AI techniques have been developed for this purpose, each possessing distinct analytical approaches, strengths, and limitations.

Table 1. Conventional vs AI – Based Dental Age Estimation

Parameter	Conventional Methods	AI – Based Methods
Analysis Type	Manual interpretation by experts	Automated computer-based analysis
Time Required	More time consuming	Faster processing
Observer Bias	High possibility of subjective variation	Reduced observer dependency
Accuracy	Moderate accuracy	Higher accuracy
Reproducibility	Variable results between examiners	More consistence and reproducible
Large Dataset handling	Difficult and time intensive	Efficient handling of large dataset
Human Expertise Needed	Requires intensive expert involvement	Minimal supervision after training
Common Approaches	Demerjian, Cameriere, Gustafson method	CNN, ANN, Machine Learning models

Machine Learning

Machine learning is a branch of artificial intelligence that enables computer systems to learn from data and improve performance without explicit programming for every task. In forensic dental age estimation, machine learning algorithms are trained using radiographic images, morphometric measurements, and clinical datasets to identify correlations between dental development and chronological age.[34] Machine learning methods generally involve two phases: training and prediction. During training, the algorithm analyzes labeled datasets in which the chronological age is already known. The system identifies patterns and generates predictive models based on these relationships. In the prediction phase, the trained model estimates the age of unknown individuals by comparing their dental features with previously learned patterns. Machine learning algorithms are particularly useful in reducing subjectivity associated with traditional manual interpretation. They can process large datasets rapidly and provide standardized outputs with improved reproducibility. However, their performance depends heavily on dataset quality, sample size, and population diversity.

Artificial Neural Networks

Artificial neural networks (ANNs) are computational models inspired by the structure and functioning of the human brain. These systems consist of interconnected processing units called neurons, which work together to analyze and interpret data. Neural networks are capable of recognizing nonlinear and complex relationships between variables, making them highly suitable for age estimation studies.[24] In forensic odontology, artificial neural networks are commonly trained using dental radiographs and age-related measurements. The network receives input data such as tooth dimensions, pulp-to-tooth ratios, or developmental stages and produces an estimated age as output. Through repeated training cycles, the model adjusts its internal parameters to minimize prediction errors and improve accuracy. ANNs have demonstrated promising performance in predicting age from panoramic radiographs and other dental imaging modalities. They are particularly effective in handling multidimensional datasets where relationships between variables may not be easily detectable using conventional statistical methods. However, neural networks often require large datasets and substantial computational resources for effective training.

Deep Learning

Deep learning is an advanced subset of machine learning that utilizes multilayered neural networks capable of automatically extracting features from complex datasets. Unlike traditional machine learning techniques that require manual feature selection, deep learning systems can independently identify important patterns directly from raw images.[32] Deep learning has become one of the most influential AI techniques in forensic age estimation because of its exceptional performance in image analysis. Dental radiographs contain intricate anatomical details and developmental patterns that may be difficult to evaluate manually. Deep learning models can analyze these images efficiently and identify subtle age-related changes with high precision. The growing availability of digital radiographic databases and advanced graphics processing units has accelerated the use of deep learning in forensic odontology. Deep learning algorithms have demonstrated high accuracy in estimating age from orthopantomograms, intraoral radiographs, and images. Convolutional neural networks (CNNs) are among the most widely used deep learning architectures in dental image analysis and forensic age estimation. CNNs are specifically designed for processing visual data and are highly effective in recognizing image patterns, textures, and anatomical structures. [18,4] A CNN consists of multiple layers that perform different computational functions, including feature extraction, pooling, and classification. During analysis, the network automatically detects important image characteristics such as tooth morphology, root development, pulp chamber size, and calcification stages. These features are then used to predict the approximate age of the individual. CNNs have shown excellent performance in analyzing panoramic radiographs because they can process entire dental images without requiring manual segmentation of individual teeth. Several studies have reported that CNN-based models achieve accuracy comparable to or greater than traditional forensic methods. Another advantage of CNNs is their ability to reduce examiner bias and inter-observer variability. Despite their advantages, CNNs require large annotated datasets for training and validation. Inadequate or biased datasets may reduce generalizability and affect predictive accuracy across different populations.

Support Vector Machine

Support Vector Machine (SVM) is a supervised machine learning algorithm frequently used for classification and regression tasks. In forensic age estimation, SVM models analyze dental features and classify individuals into specific age categories or predict chronological age values.[34] SVM algorithms are particularly effective when dealing with smaller datasets because they can generate reliable predictive boundaries between different age groups. These systems work by identifying optimal mathematical margins that separate data points according to age-related characteristics. SVM models have been applied in studies involving third molar development, pulp chamber analysis, and tooth calcification stages. Although their performance is generally good, SVMs may be less effective than deep learning methods when handling highly complex image datasets.

Random Forest Algorithm

Random forest is another machine learning technique increasingly used in forensic age estimation. This algorithm operates by generating multiple decision trees and combining their outputs to improve predictive accuracy and reduce overfitting.[6] Random forest models can analyze multiple dental variables simultaneously, including tooth measurements, pulp dimensions, and developmental stages. Because the system integrates results from numerous decision trees, it often produces stable and reliable predictions even when datasets contain variability or missing values. One advantage of random forest algorithms is their interpretability compared to some deep learning models. Researchers can identify which variables contribute most significantly to age prediction. However, the accuracy of random forest models still depends on proper dataset preparation and validation.

Regression-Based AI Models

Regression analysis remains an important component of AI-assisted age estimation. AI-based regression models analyze mathematical relationships between dental parameters and chronological age to generate predictive formulas. These systems may incorporate machine learning algorithms to improve predictive performance. Regression-based AI approaches are commonly used in adult age estimation studies involving pulp-to-tooth ratios, secondary dentin deposition, and root transparency measurements. Such models are relatively straightforward to implement and interpret, although they may not capture highly complex nonlinear relationships as effectively as deep learning systems.

Hybrid AI Models
Hybrid models combine multiple AI techniques to improve predictive performance and reliability. For example, a system may integrate convolutional neural networks for image feature extraction with support vector machines or regression algorithms for final age prediction. These combined approaches aim to utilize the strengths of different techniques while minimizing individual limitations. Hybrid AI systems have shown promising results in forensic odontology because dental age estimation often involves complex and multidimensional biological patterns. Combining algorithms may improve robustness, accuracy, and adaptability across different datasets.

Automated Image Segmentation and Feature Extraction
An important component of AI-assisted age estimation is automated image segmentation. Segmentation involves identifying and isolating relevant anatomical structures such as teeth, pulp chambers, or mandibular regions from radiographic images. Traditional manual segmentation is time-consuming and susceptible to human error, whereas AI-based segmentation systems can perform this task rapidly and consistently. Automated feature extraction further enhances age estimation by identifying relevant characteristics directly from images. These features may include tooth length, root morphology, pulp size, calcification patterns, and developmental stages. Automated extraction reduces subjectivity and improves standardization in forensic analysis.

Imaging Modalities and Databases in AI-Based Dental Age Estimation
The effectiveness of forensic dental age estimation depends greatly on the quality of imaging modalities and the availability of reliable databases. Artificial intelligence systems require large quantities of accurately labeled radiographic images for training, validation, and testing. Dental imaging provides detailed information regarding tooth development, eruption patterns, root formation, pulp morphology, and age-related degenerative changes, all of which are essential for estimating chronological age. Over the years, advancements in dental radiology and digital imaging technologies have significantly improved the ability of AI systems to analyze dental structures with greater precision and consistency. Different imaging modalities are used in forensic odontology depending on the age group, the objective of analysis, and the level of anatomical detail required. These modalities differ in image quality, radiation exposure, cost, and diagnostic capability. The integration of digital imaging with AI-based algorithms has further enhanced the speed and accuracy of age estimation procedures.

Panoramic Radiography
Panoramic radiography, also known as orthopantomography, is one of the most commonly used imaging modalities in forensic dental age estimation. A panoramic radiograph provides a two-dimensional image of the entire maxillofacial region, including both jaws, teeth, temporomandibular joints, and surrounding structures. Because all permanent teeth can be visualized in a single image, panoramic radiographs are highly useful for evaluating developmental stages and age-related dental changes.[3] In children and adolescents, panoramic radiographs allow assessment of crown calcification, root development, eruption status, and third molar maturation. AI-based systems commonly use panoramic images because they contain large amounts of anatomical information suitable for automated analysis. Deep learning algorithms, particularly models, can identify developmental patterns directly from these images without requiring extensive manual measurements. Another advantage of panoramic radiography is its widespread availability in dental hospitals and clinics. Digital panoramic systems produce standardized images that can be easily stored, transferred, and integrated into AI databases. However, panoramic radiographs also possess certain limitations. Because they are two-dimensional images, distortion and magnification may occur, especially in peripheral regions. Patient positioning errors may also affect image quality and reduce analytical accuracy.

Intraoral Radiography
Intraoral radiographs are another important imaging modality used in forensic age estimation. These images include periapical and bitewing radiographs, which provide detailed visualization of individual teeth and surrounding structures. Intraoral radiographs are particularly useful for evaluating pulp chamber dimensions, secondary dentin deposition, root transparency, and periodontal changes in adult age estimation. AI systems can analyze intraoral radiographs to identify subtle structural changes associated with aging. The high resolution of these images allows precise measurement of pulp-to-tooth ratios and other morphometric parameters. In many studies, machine learning algorithms have demonstrated promising results in estimating adult age using periapical radiographs. Despite their diagnostic value, intraoral radiographs have a limited field of view compared to panoramic radiography. Multiple images may therefore be required to evaluate the entire dentition, which can increase procedural complexity and radiation exposure. Cone Beam Computed Tomography (CBCT) has emerged as one of the most advanced imaging modalities in forensic odontology. CBCT produces three-dimensional images of dental and craniofacial structures with high spatial resolution and relatively low radiation exposure compared to conventional computed tomography.[11] The three-dimensional nature of CBCT provides several advantages for age estimation. It allows accurate evaluation of internal dental structures, including pulp chamber volume, root morphology, secondary dentin deposition, and apical closure. AI-based systems can analyze volumetric CBCT data to generate highly detailed age predictions. CBCT is especially useful in adult age estimation because age-

related changes within teeth can be measured more precisely in three dimensions than in conventional two-dimensional radiographs. Deep learning algorithms can process CBCT datasets to identify patterns associated with aging that may not be visible in standard radiographs.

However, CBCT also has limitations. The equipment is expensive and not universally available in all forensic or clinical settings. Image processing requires advanced computational resources and technical expertise. Additionally, ethical considerations regarding radiation exposure must be considered, especially when imaging living individuals solely for forensic purposes.

Computed Tomography and Magnetic Resonance Imaging

Although less commonly used than dental radiographs, conventional computed tomography (CT) and magnetic resonance imaging (MRI) have also been explored for forensic age estimation. CT imaging provides detailed cross-sectional visualization of craniofacial structures and may assist in evaluating skeletal and dental maturation simultaneously. MRI offers the advantage of avoiding ionizing radiation and has been investigated for assessing third molar development and temporomandibular joint maturation. AI systems can potentially analyze MRI datasets for age prediction, although the use of MRI in forensic odontology remains relatively limited due to high costs and lower accessibility.

Digital Imaging and Image Processing

The transition from conventional film-based radiography to digital imaging has greatly influenced AI-based dental age estimation. Digital images provide higher consistency, easier storage, rapid transmission, and improved image enhancement capabilities. Image preprocessing techniques such as contrast adjustment, noise reduction, segmentation, and normalization are commonly applied before AI analysis. Automated image processing plays an important role in improving the performance of AI algorithms. Segmentation techniques help isolate teeth, pulp chambers, and jaw structures from surrounding tissues, allowing more focused analysis. Feature extraction methods further identify relevant characteristics such as tooth dimensions, calcification stages, and root morphology. The use of digital imaging also facilitates the creation of large electronic databases required for machine learning and deep learning applications.

Databases in AI-Based Age Estimation

Databases form the foundation of AI-assisted age estimation systems. AI algorithms require extensive collections of accurately labeled radiographic images representing different age groups, sexes, and populations. These datasets are used to train models to recognize developmental and degenerative dental patterns associated with chronological age. A typical forensic dental database includes radiographic images along with demographic information such as chronological age, sex, ethnicity, and clinical history. The quality and diversity of the dataset significantly influence algorithm performance. Large datasets improve the ability of AI systems to generalize across different individuals and reduce prediction bias. [[17] Publicly available dental imaging databases are relatively limited compared to datasets in other medical fields. Consequently, many forensic studies rely on institutional databases collected from hospitals, universities, or research centers. Ethical approval and patient confidentiality are essential considerations during database development because radiographic records contain sensitive personal information.

Population-Specific Databases

One of the major challenges in dental age estimation is population variability. Dental development patterns differ among ethnic and geographical groups due to genetic and environmental influences. AI models trained using one population may therefore produce less accurate results when applied to another population. To address this issue, researchers increasingly emphasize the development of population-specific databases. These databases contain radiographic records from individuals belonging to specific demographic groups, allowing AI systems to generate more accurate predictions for those populations. Population-specific calibration is particularly important in multicultural forensic contexts.

Data Annotation and Labeling

Proper annotation is essential for effective AI training. In supervised machine learning, radiographic images must be labeled accurately with chronological age and relevant anatomical information. Some datasets also include manually identified developmental stages or segmented anatomical regions. Annotation is usually performed by experienced forensic odontologists or radiologists. However, manual labeling can be time-consuming and subject to human error. Inconsistent annotations may reduce algorithm reliability and affect predictive performance. Consequently, standardized annotation protocols are increasingly recommended in forensic AI research.

Advantages

The integration into forensic dental age estimation has significantly transformed the field of . Traditional age estimation methods often depend on manual interpretation, observer expertise, and subjective assessment of radiographic findings. Artificial intelligence introduces automated and data-driven approaches capable of analyzing large volumes of dental images with improved speed and consistency. [20] Machine learning and deep learning techniques have demonstrated promising accuracy in identifying developmental and degenerative dental changes associated with age. Despite these advancements, AI-based systems also face several scientific, ethical, technical, and practical challenges. Therefore, understanding both the advantages and limitations of AI in forensic age estimation is essential for evaluating its current and future role in forensic practice.

Improved Accuracy and Precision

One of the major advantages of AI-based age estimation is the potential for improved diagnostic accuracy. Traditional methods rely heavily on visual interpretation by forensic experts, which may vary according to experience and subjective judgment. AI algorithms, particularly models, can identify subtle anatomical and developmental patterns that may not be consistently recognized by human observers. By processing extensive radiographic datasets, AI models can recognize relationships between dental morphology and chronological age. This capability allows more precise estimation, especially when evaluating calcification stages, root development, pulp chamber changes, and secondary dentin deposition. In many studies, AI models have demonstrated prediction accuracy comparable to or even greater than conventional manual methods.

Reduction of Observer Bias

Conventional forensic dental assessment is often associated with intra-observer and inter-observer variability. Different examiners may interpret the same radiograph differently, leading to inconsistent results. AI-based systems reduce this variability by applying standardized computational procedures to all images. Because AI algorithms follow fixed analytical protocols, they provide greater reproducibility and consistency in age estimation. This standardization is particularly important in forensic investigations, where scientific reliability and objectivity are essential for legal acceptance.

Faster Processing and Automation

AI significantly improves the speed of forensic age estimation. Manual assessment of large numbers of radiographs can be time-consuming, especially in mass disaster situations or large-scale forensic investigations. AI algorithms can process hundreds or thousands of images rapidly with minimal human intervention.[16] Automated image analysis also reduces the workload of forensic experts and allows more efficient case management. Tasks such as tooth segmentation, developmental stage identification, and measurement extraction can be performed automatically, saving considerable time and effort.

Ability to Analyze Complex Patterns

Human interpretation is often limited when dealing with highly complex or multidimensional data. AI systems excel at identifying nonlinear relationships and hidden image patterns that may not be obvious during manual examination. Deep learning models are capable of extracting features directly from raw radiographic images without requiring manual measurements or predefined criteria. This enables AI to recognize subtle developmental and age-related changes with greater analytical depth. Such capabilities are especially valuable in adult age estimation, where age-related changes tend to be gradual and difficult to evaluate visually.

Applicability to Multiple Imaging Modalities

AI-based systems can be applied to a wide range of imaging modalities, including panoramic radiographs, intraoral radiographs, and images. This versatility allows forensic experts to utilize different types of dental records according to case requirements. Three-dimensional imaging modalities such as CBCT provide detailed anatomical information that AI systems can analyze efficiently. The adaptability of AI across multiple imaging platforms enhances its usefulness in forensic practice.

Continuous Learning and Improvement

Another important advantage of AI is its ability to improve continuously through retraining and exposure to additional data. As larger and more diverse databases become available, AI models can refine their predictive performance and adapt to different populations. Unlike static traditional methods, AI systems are dynamic and capable of evolving over time. Continuous algorithm updates may improve accuracy, reduce bias, and expand forensic applications in the future.

Potential for Population-Specific Models

Population variability represents a major challenge in forensic age estimation because dental development differs among ethnic and geographical groups. AI systems can be trained using population-specific datasets, allowing the development of tailored predictive models for particular demographic groups. This adaptability enhances forensic accuracy and may reduce errors associated with applying generalized standards across diverse populations.

Support in Medico-Legal Decision Making

AI-assisted systems can provide supportive evidence in legal and forensic contexts. Automated analysis and objective measurements may strengthen the scientific credibility of forensic conclusions. In cases involving disputed age, immigration, child labor, sports eligibility, or criminal responsibility, AI-based methods may assist experts in making more reliable assessments.

LIMITATIONS

Dependence on High-Quality Data

The performance of AI systems depends heavily on the quality and quantity of training data. Poor-quality radiographs, inconsistent imaging protocols, or inaccurate annotations can negatively affect algorithm accuracy.[17] Many forensic studies use relatively small datasets collected from limited populations, which may reduce the generalizability of AI models. If the training data are incomplete or biased, the resulting predictions may be unreliable.

Population Bias and Generalizability Issues

Dental maturation patterns vary among populations due to genetic, environmental, nutritional, and socioeconomic factors. AI models trained using one population may not perform equally well in another demographic group.This limitation poses a major challenge in global forensic practice, where diverse populations are encountered. Without proper population-specific validation, AI systems may produce inaccurate age estimates.

Black Box Nature of Deep Learning
Critics often point out that deep learning is a bit of a 'black box'. Even if the AI gives you a perfectly accurate age, it's hard to see exactly how it got there. that's a big problem in the court, here a judge expects you to explain your reasoning, not just hand over a computer's guess.[27] In forensic and legal settings, transparency and explainability are extremely important. Courts and legal authorities may question conclusions generated by systems whose internal decision-making processes are not fully understandable. This lack of interpretability remains a significant obstacle to widespread legal acceptance.

Ethical and Privacy Concerns
AI-based forensic systems require access to large quantities of radiographic and personal data. The collection, storage, and sharing of such information raise important ethical and privacy concerns. Patient confidentiality must be protected through anonymization and secure data management practices. Unauthorized use or misuse of forensic databases could result in ethical and legal complications.

Requirement for Advanced Infrastructure
Implementation of AI systems often requires advanced computational resources, specialized software, and technical expertise. High-performance computers and graphics processing units may be necessary for training complex deep learning models.[1] In developing regions or resource-limited forensic laboratories, access to such infrastructure may be limited. Consequently, widespread implementation of AI-based forensic systems may face economic and logistical barriers.

Risk of Overfitting
Overfitting occurs when an AI model performs well on training data but poorly on new or unseen datasets. This problem arises when the algorithm becomes too closely adapted to the specific characteristics of the training dataset. Overfitted models may demonstrate high apparent accuracy during development but fail to produce reliable results in real forensic situations. Proper validation and external testing are therefore essential before clinical or forensic implementation.

Limited Standardization
Although AI research in forensic odontology is growing rapidly, standardized protocols for image acquisition, annotation, algorithm development, and validation are still lacking. Different studies often use varying methodologies, datasets, and evaluation criteria, making direct comparison difficult. The absence of universal standards may hinder reproducibility and limit the integration of AI into routine forensic practice.

Legal and Regulatory Challenges

The medico-legal acceptance of AI-generated evidence remains uncertain in many jurisdictions. Questions regarding accountability, reliability, and admissibility must be addressed before AI systems can be fully integrated into forensic investigations. If an AI system produces an incorrect age estimate, determining legal responsibility may become complex. Regulatory frameworks governing AI use in forensic science are still developing and vary across countries.

Inability to Replace Human Expertise
Despite their advanced capabilities, AI systems cannot completely replace forensic experts. Human judgment remains essential for interpreting findings, correlating clinical information, and considering contextual factors that may influence age estimation. Artificial intelligence is best considered a supportive technology that complements, rather than replaces, forensic expertise. The most effective approach involves collaboration between AI technologies and experienced forensic odontologists.

Table 2. Common Imaging Modalities Used in AI – Based Dental Age Estimation

Imaging Technique	Features	Advantages	Limitations
Orthopantomogram (OPG)	Provides panoramic of teeth and jaws	Widely available and commonly used	Lower image detail compared to 3d imaging
Cone Beam Computed Tomography (CBCT)	Produces three-dimensional dental images	High precision and detailed anatomical visualization	Higher radiation dose and expensive
Intraoral Radiograph	Captures detailed image of specific teeth	High image clarity for individual teeth	Limited field of view
Magnetic Resonance Imaging (MRI)	Visualizes soft tissues without radiation	No ionizing radiation exposure	Expensive and less accessible
Computed Tomography (CT) scan	Detailed cross- sectional imaging	Accurate structural assessment	High radiation exposure and cost

Future Perspectives
The integration of into is expected to transform dental age estimation from a predominantly manual and observer-dependent procedure into a highly automated, standardized, and data-driven forensic practice. Although current AI-based systems have already demonstrated promising levels of accuracy and efficiency, future advancements are likely to further enhance their reliability, applicability, and global acceptance in medico-legal investigations. One of the most significant future directions involves the development of more sophisticated deep learning architectures capable of performing fully automated age estimation with minimal human

intervention. Existing models often require manual preprocessing or annotation of dental images, which can introduce variability and reduce efficiency. Future systems are expected to integrate automated tooth segmentation, feature extraction, and age prediction into a single workflow, thereby improving consistency and reducing operational time.[32] The increasing use of and hybrid deep learning frameworks may enable forensic experts to achieve more precise estimations even in complex cases involving mixed dentition, pathological conditions, or poor-quality radiographs. Another important area of advancement is the incorporation of multimodal imaging and data integration. Future AI systems may combine information obtained from orthopantomograms, cone beam computed tomography, cephalometric radiographs, and intraoral scans to generate more comprehensive and accurate age predictions. The integration of dental data with skeletal, genetic, and biometric information may further improve the predictive capability of forensic age estimation models. Such multidisciplinary approaches could prove particularly beneficial in disaster victim identification and immigration-related forensic examinations where high levels of precision are required. The availability of large-scale and ethnically diverse datasets will also play a crucial role in the future development of AI-driven age estimation. Many currently available models are trained using limited population-specific datasets, restricting their universal applicability. Future research should focus on establishing international forensic dental databases containing standardized radiographic records from individuals of different age groups, ethnicities, and geographic regions. Such databases would facilitate the training of more generalized and unbiased AI models capable of producing accurate results across diverse populations. We're also starting to hear more about 'Explainable AI'. This could be a total game changer for forensics because it helps pull back the curtain on how these models work, making the evidence much easier to trust in a legal setting.[27] One of the major concerns associated with deep learning models is the "black-box" nature of their decision-making process, which may create difficulties in legal and courtroom acceptance. Future explainable AI frameworks are expected to provide visual and analytical interpretations of how predictions are generated, thereby increasing transparency, trust, and admissibility in judicial proceedings. The ability to justify AI-generated conclusions with understandable evidence will be essential for medico-legal credibility. Cloud-based forensic platforms and real-time AI applications are also likely to become increasingly important. With advancements in digital dentistry and tele forensics, forensic experts may be able to upload dental radiographs to secure cloud systems and obtain rapid age estimations remotely. Such technologies could improve accessibility in regions with limited forensic infrastructure and facilitate faster forensic responses during mass disasters or humanitarian crises. Despite these promising developments, future progress will depend heavily on the establishment of ethical guidelines, legal regulations, and international standardization protocols. Researchers and forensic professionals must ensure that AI systems are developed responsibly, with careful consideration of data privacy, algorithmic bias, informed consent, and reliability. Collaborative efforts between forensic odontologists, radiologists, computer scientists, legal authorities, and policymakers will be necessary to ensure the safe and effective integration of AI into routine forensic practice.

CONCLUSION

Dental age estimation remains one of the most important components of forensic identification due to the durability, uniqueness, and predictable developmental changes of dental tissues throughout life. At the end of the day, teeth remain one of the best ways to figure out someone's age because they are so durable and predictable. While the old – school manual methods have served us well for decades, they're often slow and depend too much on an expert's personal opinion. AI is changing that by bringing in a level of speed and accuracy that was previously impossible. The emergence of artificial intelligence has introduced a new dimension to forensic odontology by enabling automated, rapid, and highly accurate analysis of dental structures. Machine learning and deep learning techniques have demonstrated considerable potential in improving the precision and reproducibility of age estimation procedures through the analysis of dental radiographs and three-dimensional imaging modalities. [32,18] AI-assisted systems are capable of processing large datasets, identifying subtle patterns that may not be visible to human observers, and minimizing human bias in forensic evaluations. Although AI-based dental age estimation has shown remarkable progress, several challenges still remain. Limitations related to dataset diversity, imaging quality, algorithm transparency, ethical concerns, and lack of standardized validation protocols continue to restrict widespread forensic implementation. On the top of that , the medico-legal acceptance of AI-generated results requires scientifically validated, explainable, and reproducible systems that can withstand judicial scrutiny. Overall, the application of artificial intelligence in forensic odontology represents a rapidly evolving and promising field with the potential to significantly strengthen forensic age estimation practices. With continued advancements in imaging technologies, computational methods, and interdisciplinary collaboration, AI-driven systems may soon become an integral component of routine forensic investigations. Future research focused on standardization, explainability, and population-inclusive datasets will be essential for ensuring the reliability, fairness, and global applicability of these technologies in medico-legal contexts. [30,17]

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