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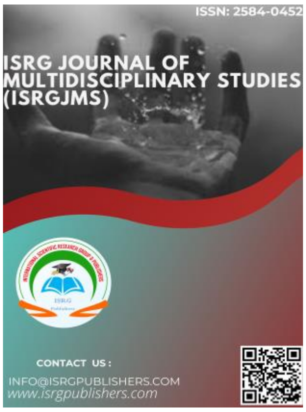

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Historical Perspective and Recent Advances in Dental Age Estimation in Forensic Anthropology: A Review

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Abstract

Age is one of the essential factors, which play an important role in every aspect of life. Human identification is an important aspect of forensic medicine and dentistry. Age, sex, stature, and race or ancestry are the 'big four' which form the central focus of forensic anthropology and taphonomy. Chronological age, as recorded by registration of birth date, remains a significant factor in medico-legal jurisprudence and socio-political relevance. Dental age is considered to be vital in establishing the age of an individual as tooth development patterns are predictable and also showed strong correlation to chronological age. Different morphological stages of mineralization correlate with the different developmental stages. This review explores the historical development of dental age estimation methods, their application across different age groups, and the recent advances in dental age estimation techniques.

Keywords: *dental age estimation, historical perspectives, recent advances, forensic anthropology.*

INTRODUCTION

The forensic identification of individuals who died, either through mass fatalities involving fragmented remains or single unexpected deaths, remains an essential process in the field of medicolegal investigation. Forensic anthropology has a critical role in legal and investigative processes, particularly in identifying unknown human remains. One of the essential aspects of forensic anthropology is age estimation, which provides crucial information for identification purposes (Priyadarshini et al., 2015). Dental age

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estimation stands out as a reliable method due to the relatively predictable pattern of dental development and its resistance to postmortem changes. Determining the age of a deceased individual has been an area of focus for forensic anthropologists and scientists for many years, with numerous techniques and methods having been developed. One such method, Forensic Odontology, involves the use of teeth to estimate age. This method has gained significant traction due to teeth's remarkable ability to withstand postmortem degradation, deterioration, and extreme environmental changes better than most human tissues (Ubelaker and Khosrowshashi, 2019).

In many cases, chronological age and biological age may not be the same, due to the developmental variations. Hence, different parameters such as dental age, bone age, mental age, and other factors such as menarche, voice change, height, and weight are considered as proxy indicator for biological age and body development (McKenna et al., 2002). Dental development is more reliable as an indicator of biological maturity in children. Dental maturity is more relevant as it is less affected by nutritional and endocrine status.

The estimation of age in various age groups, including neonates, adolescents, and adults, is possible using the teeth as a marker. In this article, we will be focusing on the different dental age estimation methods that has been used to estimate age in all age groups, their accuracies and limitations and recent advances in this area.

History of Dental age estimation methods

Dental age estimation is a crucial aspect of forensic anthropology, providing valuable information for the identification of individuals, both living and deceased. This historical review traces the development of dental age estimation methods from early observational techniques to contemporary advanced methodologies.

Early Observational Techniques

19th Century Beginnings

The earliest attempts at dental age estimation can be traced back to the 19th century. Dentists and anatomists began observing the patterns of tooth eruption and loss as indicators of age. These initial observations were largely anecdotal and lacked a systematic approach.

One of the first systematic studies was conducted by Dr. John Allen, who published "A Practical Treatise on the Management of the Teeth" in 1834. Allen observed the sequence and timing of tooth eruption in children, noting the potential of these patterns to estimate age (Allen, 1834).

Development of Dental Charts

Schour and Massler (1941)

The mid-20th century marked a significant advancement in dental age estimation with the work of Schour and Massler. In 1941, they developed comprehensive dental development charts that depicted the stages of tooth formation and eruption from infancy to adolescence. These charts became foundational tools in both clinical and forensic settings, offering a visual representation of dental development (Schour & Massler, 1941).

Moorrees, Fanning, and Hunt (1963)

Further refinement came with the work of Moorrees, Fanning, and Hunt in 1963. They provided a more detailed assessment of tooth formation stages and introduced measurements of both tooth emergence and crown-root formation. Their method allowed for more precise age estimates with narrower confidence intervals, enhancing the reliability of dental age estimation (Moorrees, Fanning, & Hunt, 1963).

Application of radiographs in dental age estimation

Radiological imaging plays a crucial role in the field of dental age estimation. The radiological approach to dental age estimation involves analyzing the radiographs of teeth and assessing their developmental stages. This approach has been widely used due to its accuracy, reliability, and non-invasiveness. In recent years, developments in machine learning and artificial intelligence have further improved the accuracy of radiological imaging in dental age estimation (Maruyama et al., 2021).

The radiological approach to dental age estimation has been widely studied, and a variety of imaging techniques have been used to assess dental development. The most commonly used imaging modalities include panoramic radiography, cephalometric radiography, and cone-beam computed tomography (CBCT). Each of these techniques has its unique advantages in terms of image resolution, field of view, and radiation exposure. Recent studies have shown that CBCT has high accuracy in determining dental age and is a useful tool for identifying developmental abnormalities in patients (Wasilewski et al., 2020). Radiological imaging in dental age estimation has also been used in forensic dentistry to aid in the identification of human remains. Radiographs of teeth can provide vital information about the age, sex, and ancestry of the individual. The use of radiological imaging in forensic dentistry has become increasingly important due to the large number of cases involving unidentified human remains. In such cases, radiological imaging can help to establish the identity of the individual by providing information about their dental records and developmental stages (Eva et al., 2022; Nilima et al., 2020)

Radiation exposure from radiological imaging techniques such as CT scans and x-rays poses a potential risk for cancer, which is a major concern, especially in pediatric and young adult populations (Christos et al., 2004; Tyagi et al., 2022). This concern has led to the development of radiation dose reduction protocols for radiological imaging, including the use of low-dose imaging protocols and the reduction of unnecessary imaging procedures (Hillis, 2014). It is essential to balance the potential risks associated with radiation exposure and the benefits of using radiological imaging techniques for dental age estimation.

However, radiological techniques have become an essential tool for dental age estimation due to its non-invasive nature, reliability, and accuracy. Radiological imaging techniques, including computed tomography (CT) and magnetic resonance imaging (MRI), have been used to determine the dental age of individuals with varying degrees of success (Sundin, Wills, & Rockall, 2015).

Scoring Methods of Dental Age Estimation using orthopantomograms

Dental age estimation methods have gone through various stages and methods of evaluation with different researchers attempting to obtain the most reliable methods of estimating age using the teeth. The scoring method unlike the atlas method employed the use of measured parameters to estimate age. This include but not limited to the Demirjian, Ikeda, Gustafson, Cameriere, Willem, Nolla, Drusini and Haavikko's methods. The Demirjian method, widely

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acknowledged and utilized, relies on a thorough examination of dental development stages. Ikeda's method places emphasis on the patterns of tooth mineralization, offering valuable insights for determining chronological age. Similarly, the Gustafson method concentrates on dental attrition and the formation of secondary dentin, providing an additional viewpoint. Cameriere's method meticulously examines tooth roots and apices, thereby enhancing the accuracy of age assessment. Willem's method, Nolla's method, Drusini's methods, and Haavikko's method each introduce specialized techniques and criteria, enriching the resources available to dental professionals engaged in age estimation.(De Donno et al., 2021).

The Demirjian Method

A French dentist named Dr. Alexandra Demirjian in 1973 unveiled a new approach of estimating age using panoramic radiographs. The technique is frequently applied to forensic dentistry and to determining a child's or adolescent's dental age. (Mohamed et al., 2023). This approach utilizes the seven permanent mandibular teeth on the left side, excluding the third molar. The Demirjian method outlines eight stages of tooth calcification from stage A to stage H, where stage 0 indicates no visible tooth calcification in the panoramic image (Chinna & Chinna, 2019). It evaluates the development of the central incisors, lateral incisors, canines, first premolars, second premolars, first molars, and second molars. Additionally, the scoring system for this method varies between boys and girls. (Kurniawan et al., 2022)

Demirjian dental formation stages

Dental formation stages according to Demirjian are as follows:
Stage A: Occlusal point calcification, without fusion of other calcification parts,
Stage B: The fusion of the mineralization point where the occlusal surface contoured the teeth is already seen,
Stage C: Calcification of the dental crown has been completed and dentin disposition starts,
Stage D: The formation of the crown has been completed,
Stage E: The root length of the teeth is shorter than the crown height,
Stage F: The root length of the teeth exceeds the crown height,
Stage G: The formation of the root has been completed, but the apical foramen is still open,
Stage H: Apical foramen was closed.

The stages serve as markers for the dental development of each tooth. Typically, distinctions in dental maturity between males and females do not become apparent until around the age of 5. Each stage of mineralization receives a numerical score, offering an approximation of dental maturity on a percentile scale ranging from 0 to 100 (Fatma et al., 2017). These maturity scores (S) for all teeth are summed, and the cumulative maturity score can be directly translated into a dental age using a standardized table, or alternatively, they can be inputted into regression formulas. Separate formulas exist for girls and boys. For females, the formula is as follows:

$$\textbf{Age} = (0.0000615 \times S^3) - (0.0106 \times S^2) + (0.6997 \times S) - 9.3178$$

And in males, the formula is:

$$\textbf{Age} = (0.000055 \times S^3) - (0.0095 \times S^2) + (0.6479 \times S) - 8.4583$$

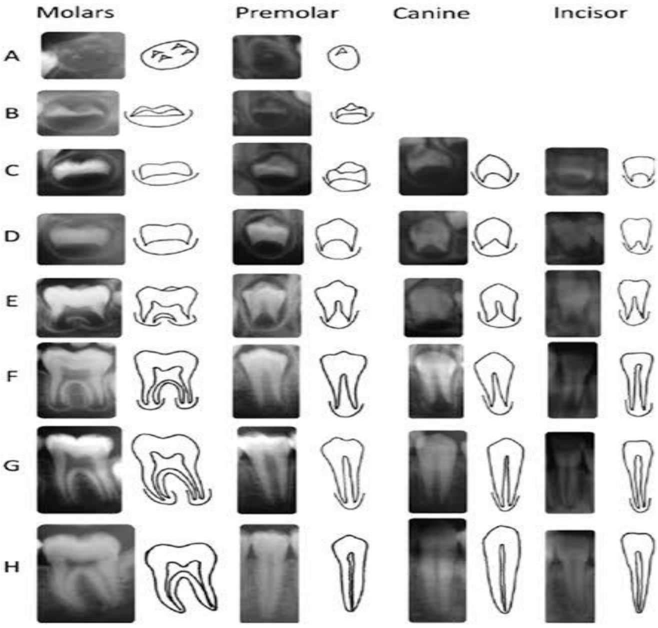

Figure 1: Demirjian's stages of tooth development for dental age estimation.

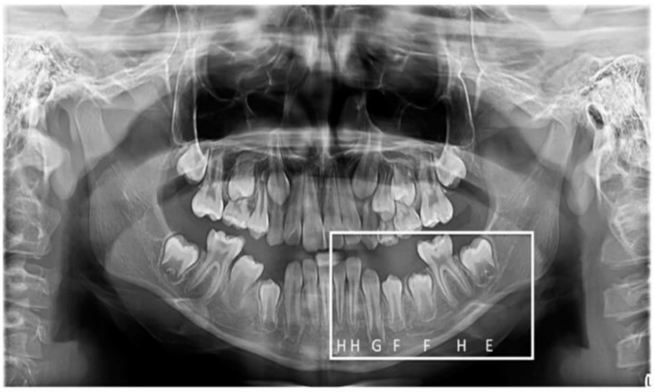

Figure 2: Panoramic radiograph displaying dental age assessment in age estimation using the Demirjian method.

Limitations of Demirjian's method of dental age estimations (Chinna & Chinna, 2019)

1. The Demirjian method relies on orthopantomograms, which are challenging to obtain in young children due to technical limitations and ethical concerns.
2. Since this technique necessitates the simultaneous assessment of seven left mandibular teeth, it cannot be utilized in children who have missing teeth, whether congenital or acquired.
3. This approach may fail to indicate tooth agenesis, distinct delays in dental growth (excluding third molars), and the presence of systemic diseases, as well as various developmental stages of the teeth.
4. Determining the developmental stage of teeth may pose difficulties as it involves subjective judgment, making the choice of developmental stage somewhat ambiguous.

The Ikeda's method

In 1985, Ikeda and his team presented a pioneering concept in dental analysis with the introduction of the tooth-coronal index (TCI). This innovative index revolutionized the field by utilizing two crucial linear measurements obtained from dental radiographs of extracted human teeth: the crown height (CH) and the coronal pulp cavity height (CPCH). By incorporating these precise

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measurements, the TCI offered a comprehensive framework for evaluating dental structures, providing invaluable insights into tooth morphology and development. This approach not only enhanced diagnostic accuracy but also facilitated a deeper understanding of dental anatomy and pathology, thereby contributing significantly to the advancement of dental science and clinical practice (Gotmare et al., 2019). A direct line drawn from the cementoenamel junctions on the mesial and distal sides marks the boundary between the anatomical top and bottom of the tooth. The crown height (CH) was gauged by measuring from the base of the neck to the highest point of the cusp, while the crown-pulp chamber height (CPCH) was measured from the neck base to the highest pulp horn tip. Subsequently, the tooth coronal index (TCI) was computed using the formula: TCI = (CPCH × 100) / CH. (Jeon et al., 2014)

Ikeda's approach also validated the inverse relationship between TCI and age through the assessment of lower premolars and molars using panoramic radiographs. Linear regression equations were formulated, yielding correlation coefficients ranging from -0.92 (molars, aggregate sample, right side) to -0.87 (molars, female) (Hatice et al., 2017).

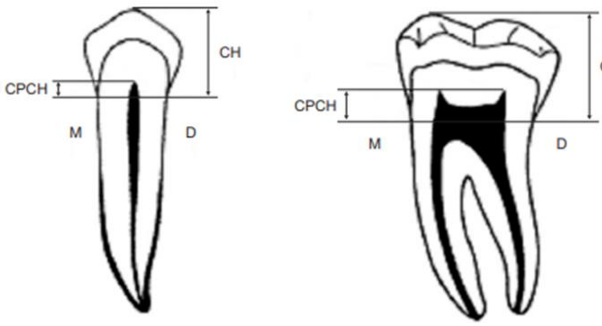

Figure 3: Schematic representation of tooth measurements taken off a dental radiograph.
Note: The straight line traced between the distal (D) and mesial (M) enamel. CH, coronal height; CPCH, coronal pulp cavity height. Tooth-coronal index (TCI)= CPCH×100/CH.

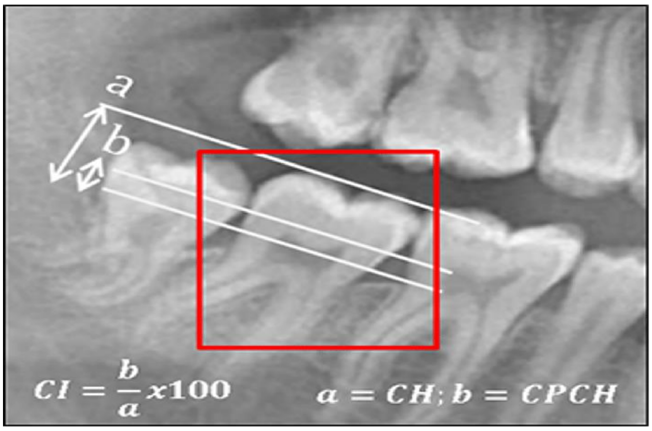

Figure 4: A dental panoramic X-ray of teeth displaying tooth measurements used to calculate the tooth coronal index.

Note: CI (Tooth coronal index), CH (a) (Crown height), CPCH (b) (Coronal pulp cavity height)

Cameriere's Method

Roberto Cameriere applied the Cameriere's technique in 2006, utilizing panoramic radiography for age estimation by assessing the ratio between the length of open apices projection and the major axis of tooth length, commonly referred to as the open apices method.(Nadia et al., 2023). This approach focuses on the seven left mandibular teeth. Initially, closed apices teeth are identified and counted, represented by N0. For the remaining teeth with open apices, the measurement involves the distance between the inner sides of the open apex for single-root teeth or the sum of distances for multi-root teeth. These measurements, abbreviated as Ai (i = 1–7), are then normalized by dividing them by the respective tooth length (Li, i = 1–7) to yield xi = Ai/Li. Subsequently, a variable S is calculated as the sum of N0 and xi (Fig. 5). This value is incorporated into the age estimation formula:

Age = 8.971 + 0.375g (where gender is denoted by 1 for boys and 0 for girls) + 1.631 × 5 + 0.674N0 − 1.034s − 0.176sN0. In 2007, the method was revised to Age = 8.387 + 0.282g − 1.692 × 5 + 0.835N0 − 0.116s − 0.139sN0 (Hostiuc et al., 2021).

Numerous researchers have developed methods utilizing this approach, tailored to specific populations, resulting in the derivation of distinct regression equations and the exploration of novel research avenues (Balla et al., 2019). Furthermore, various studies have demonstrated the superior accuracy of this method in age estimation when compared to alternative methodologies such as Demirjian, Nolla, Haavikko, or Willems methods. Nevertheless, the average variance between chronological age and dental age estimated by this technique has been found to fluctuate across different studies, even those conducted on similar demographics. Additionally, investigations that assessed mean differences across various age groups have revealed varying levels of precision contingent upon the subjects' age. However, the statistical significance of these findings often remains undetermined due to limited case numbers within each age bracket (Ozveren & Serindere, 2018).

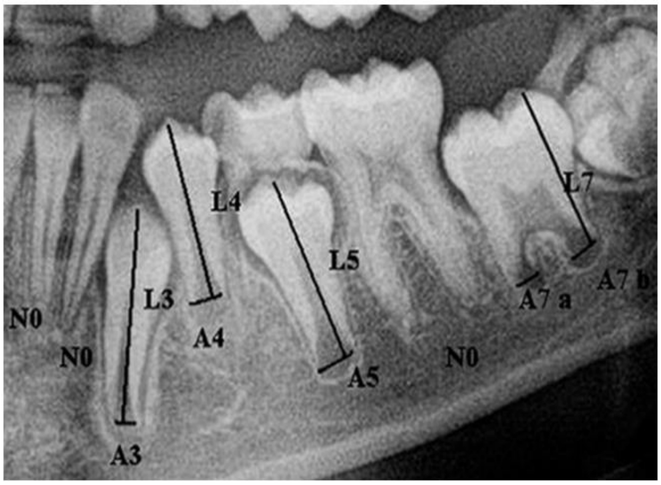

Figure 5: An example of tooth measurement. Ai, i=1,..., 5 (teeth with one root), is the distance between the insides of the exposed root apex; Ai, i=6, 7 (teeth with two roots), is the sum of the distance between the outer edges of the two exposed roots; and Li, i=1,... 7, is the length of the seven teeth.

The Willem's Method

Willems devised an adaptation of Demirjian's method, refining the scoring system after noticing significant overestimations. The Willems method employs an adapted rendition of Demirjian's technique, which involves analyzing patient radiographs to categorize tooth development into eight distinct stages. Each tooth's developmental stage is evaluated based on a gender-specific reference table, and the scores for seven designated teeth are aggregated. This cumulative score directly corresponds to dental age (DA) (Fig. 6) (Koç et al., 2021). This approach facilitates a

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comprehensive assessment of dental maturity, utilizing gender-specific criteria to accurately determine developmental stages and provide a direct estimation of dental age based on radiographic findings. Extensive evaluation across diverse populations has demonstrated the superior accuracy of this modified method compared to Demirjian's original.(Rath et al., 2017) Recent studies have consistently shown Willems' method to outperform the conventional approach, with minor overestimations of 0.0 years in males and 0.2 years in females. This enhanced technique marks a significant advancement in age estimation methodology, offering greater precision across various demographic groups (Cherian et al., 2020).

Figure 6: The development stages of each tooth according to the Willems method.

The Nolla's Method

In 1960, Nolla introduced a method for assessing tooth development by dividing the process into ten distinct stages, each assigned a categorical number for identification.(Mohamed et al., 2023) This method involves evaluating the mineralization of permanent dentition, where a patient's radiograph is compared to a standardized reference figure (Fig. 7). Each tooth in both the upper and lower arches is then assigned a stage, with the cumulative stages matched against Nolla's reference table (Zirk et al., 2021). One notable advantage of Nolla's approach is its versatility, as it can be applied to individuals with or without third molars, and it accounts for differences between males and females. Additionally, researchers using Nolla's method can choose from a range of ten stages, with three intermediate options available for each stage (Mohamed et al., 2023).

However, the inclusion of a larger number of stages may introduce complexity and potentially decrease the method's precision during assessments. Despite this drawback, Nolla's method remains a valuable tool in dental research for evaluating tooth development and age estimation (Paz Cortés et al., 2019).

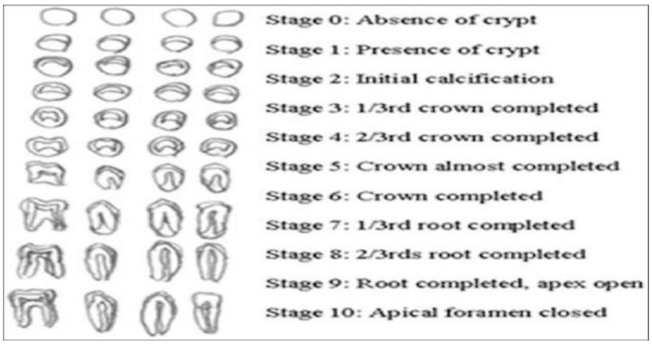

Figure 7: Dental development chart by Nolla.

The Haavikko's Method

Haavikko pioneered the dental age estimation method, focusing on both maxillary and mandibular teeth. This approach involves assessing 12 distinct radiographic stages, with six stages pertaining to crown formation and six to root formation. Additionally, a stage labeled "O" is designated for the emergence of a tooth crypt (Fig. 8). This method encompasses incisors to second molars in both the upper and lower jaws, providing a comprehensive framework for age determination based on dental development (Chaudhry et al., 2020).

This method proves valuable when assessing dental age, especially in cases where any of the permanent teeth is absent. Although various dental age estimation methods revealed a high degree of accuracy and reliability specific to a population group, ethnic differences between various population groups are found to affect the accuracy and reliability of different dental age estimation methodologies. However, the concept of ethnic variability in dental age estimation methods is still unclear, as the reports of testing ethnic variability in dental age estimation have come with no significant results (Chaudhry et al., 2020).

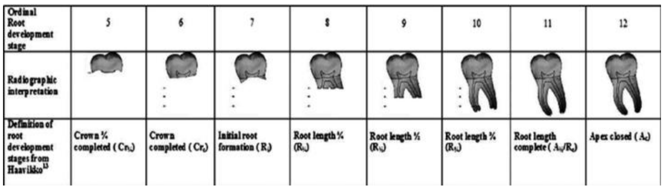

Figure 8: Image displaying the twelve radiographic stages of tooth development for age estimation by Haavikko.

Atlas Method of Dental Age Estimation

In situations of a mass disaster, the need for an accurate, reliable, cost-effective, fast and easy to use technique is imperative for the victim identification process, especially when the lack of personnel or resources dictates the help of non-trained volunteers. In these cases, using a comparison method in the form of a diagram (atlas) or computer software with the radiograph of developing teeth that would give an estimate of chronological age would be ideal (AlQahtani, 2012).Atlas methods provide an easy and reliable means of dental age estimation without many technicalities involved. The London atlas is said to be most widely used in many climes, however, the Wits atlas is reputed to be population specific and more applicable to the African population (Esan, 2017; Esan & Schepartz, 2018).

The Atlas method is a commonly used method for dental age estimation, which involves using a set of reference images called atlases to compare and match the appearance of a person's teeth. There are several atlases available for dental age estimation, including the London Atlas, the Wit Atlas, the Schour and Massler atlas, and the Ubelakar's atlas. Each of these atlases has its unique features and suitability.

The Schour and Massler Atlas

The Schour and Massler (1941) atlas is one of the earliest dental aging charts. It provides a sequence of 21 drawings describing stages of dental development from in-utero to adulthood. The drawings show developing teeth and their eruption status in relation to an undefined line (possibly the gingival line and a corresponding age (AlQahtani et al., 2014). The age categories are arranged in consecutive years to the age of 12 years, after which the next age group is 15 years. The last two drawings show fully emerged and formed teeth at 21 and 35 years (Fig. 9). This atlas

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has been criticized because of its many inherent ambiguities. AlQahtani et al. (2014) emphasized that very few details of the sample from which the chart was derived are known.

The chart appears to have been based on dental development of terminally ill American children (the source for the very young age cohorts), although it probably incorporates data from other anatomical and radiographic sources, including the important early work of Logan and Kronfeld (1933) on Chicago children. Furthermore, there is no information on the subjects and how they were analyzed, the tooth stages and eruption level are undefined, and the age range of the subjects is limited. B. H. Smith (1991) pointed out that 19 of the possible totals of 29 subjects were younger than 2 years of age. Other limitations of the chart are the observed poor correlation with measures of skeletal age, and the combining of boys and girls together in the tooth development charts (Esan & Schepartz, 2018). Several aspects of this atlas have been criticized including no information of the material nor method of analysis, undefined tooth stages and eruption level, and small age ranges.

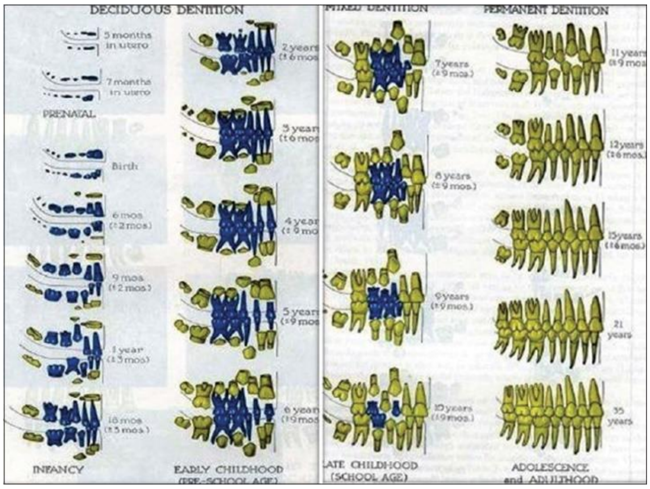

Figure 9: Schour and Massler's chart of dental age estimation.

Moorress, Fanning and Hunt's chart.

The Moorrees et al. 1963 chart, also known as the Moorrees–Fanning–Hunt dental age estimation method, is a widely used chart in forensic odontology and anthropology for estimating the age of children and adolescents based on the development of their teeth. This method is particularly useful for age estimation when only dental evidence is available. The chart is based on the observation of different stages of dental development, including the formation and eruption of teeth. It identifies and categorizes these stages for both primary (baby) and permanent (adult) teeth.

The method has been validated and is considered accurate for age estimation within certain populations. However, the accuracy can vary depending on genetic, nutritional, and environmental factors that influence dental development. The Moorrees's chart is a valuable tool for estimating age based on dental development, providing a systematic approach to understanding and documenting the growth stages of human teeth.

The Ubelaker's atlas

Ubelaker (1978) revised the Schour and Massler atlas to reflect the different developmental timing that he observed in Native American archaeological samples. His chart has improvements over the Schour and Massler atlas (Smith, 2005). He adjusted the error ranges and the original graphical descriptions of the rates of eruption and tooth formation, most especially the development of the canine from the age of 18 months to 2 years (Fig. 10). Ubelaker's use of published results on dental development of prehistoric Native Americans and other non-European populations made his chart popular for use in bioarcheological populations. He included numerous published sources to correct the age range for each drawing and defined the line as gingival emergence. He included tooth emergence of North American Indians by using "the early end of the published variation" as "some studies suggest that teeth probably form and erupt earlier among Indians." The chart was modified by Blenkin and Taylor (2012) for use on Australians. They included separate schemes for females and males and adjustments to the age range of each drawing based on their population-specific data (Ubelaker & Khosrowshahi, 2019).

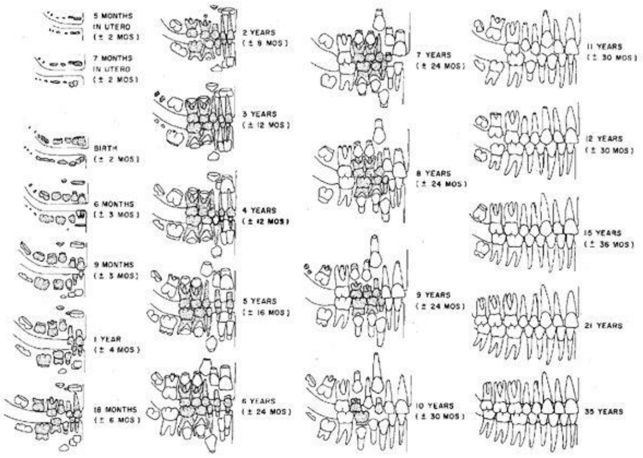

Figure 10: Ubelaker's Chart of dental age estimation

The London Atlas

The London atlas was developed in 2010 by Dr. Sakher AlQahtani at the Queen Mary University and London School of Medicine and Dentistry to estimate age through comparison with radiographic sample of teeth for ages 30 weeks to 23 years. It is a series of drawings of dental development for 31 age categories from birth to 23 years of age. All 31 diagrams that represent median stages of dental development and alveolar eruption were compiled to form the London Atlas of tooth development (Fig. 11). A spiral flow schema was designed beginning with the 30 weeks in utero diagram that is underlined with an arrow to demonstrate the ongoing development up to the age of 15 years; this is a departure from the columns used historically in previous schemas. Third molar development between the ages 16 and 23 were presented separately in a column on the side of the atlas for easy reference and the diagrams included only the second and third molars as all other teeth have reached maturity. The London atlas can assess age from 28 weeks in utero up to 23 years.

The London atlas is currently the most widely used chart for forensic and anthropological purposes. It was developed to overcome some of the limitations of previous systems (AlQahtani et al., 2014) and it was designed for global use. The London atlas is based on skeletal samples from Portugal, The Netherlands, Canada and France, with additional data from panoramic radiographs of living children of Bangladesh and British origin. AlQahtani et al. (2014) showed that the London atlas is better at estimating dental age compared to the Schour and Massler (1941) and Ubelaker (1978) charts. The atlas is tooth specific and illustrates tooth development and eruption for 31 age categories. Tooth stages and

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eruption levels are both described and illustrated. Another advantage of the London atlas is that the teeth are spaced such that each tooth is clearly visible ((AlQahtani et al., 2010)). A limitation is the combining of data on children from different populations despite the well-established pattern of population variation in tooth formation.

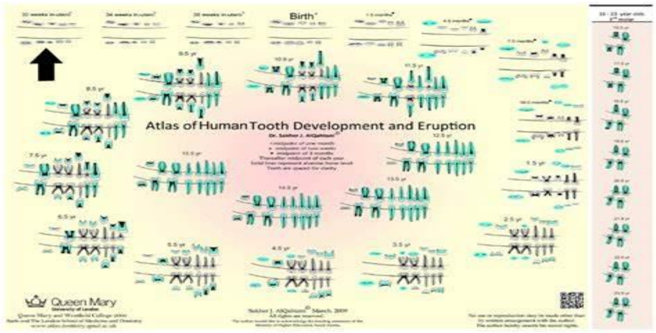


Figure 11: Atlas of human tooth development and eruption.

Note: The arrow indicates the starting point. The dentine is presented in gray for deciduous teeth and in green for permanent.

The WITS Atlas

The WITS atlas was modelled after the London atlas with two key differences. The London atlas was developed using the Moorrees method (Moorress et al., 1963) while the WITS atlas used the Demirjian method (Esan, 2017) to determine tooth developmental stages. . It is preferred because of the increased sensitivity and specificity of its crown and root development stages. While the Moorrees method has more stages for scoring, the Demirjian method uses more precisely defined stages of formation for greater refinement of scoring. The WITS atlas illustrates considerable differences in both the timing of emergence and the stages of tooth formation (Fig. 12). The WITS atlas has been demonstrated to be more suitable for the Black Southern African children than the London atlas with the London atlas overestimating age when compared with the WITS atlas. When compared to the London atlas, the canines, premolars and second molars are at least a year ahead in the WITS Atlas. Third molar formation and emergence occur three years earlier in the WITS Atlas. For example, (Esan & Schepartz, 2018)), reported that third molars emerge at age 15.5 years and are in occlusion at 17.5 years in the Southern African children whereas third molars emerge four years later and roots not complete until 21.5 years using the London atlas.

The number and magnitude of differences in the timing and stages of permanent tooth emergence and formation between the WITS and the London atlases demonstrate that the London atlas is not suitable for age estimation of Black Southern Africans. This is particularly true for forensic applications where the level of accuracy needs to be within 6 months or at most one year (Esan, 2017)

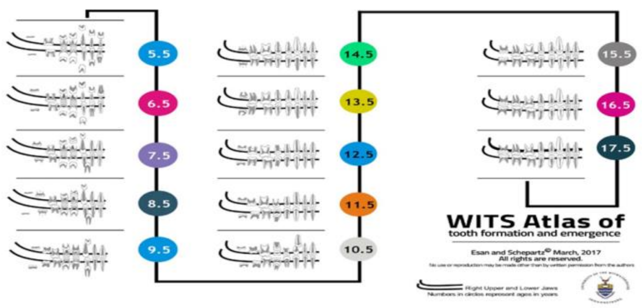


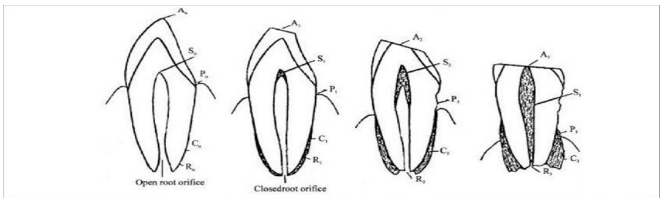
Figure 12: WITS atlas of human tooth development. Showing landmark features for estimation of dental age.

DENTAL AGE ESTIMATION FROM TOOTH MORPHOLOGY

The Gustafson's Method (1950)

Gosta Gustafson introduced the initial technique for estimating age by examining specific regressive changes in teeth between 1947 and 1950. This approach, known as morpho-histological analysis, specifically targets single-rooted teeth. (Verma et al., 2019). The age-related changes identified include; Enamel attrition (A), Formation of secondary dentin (S), Alteration or recession of the periodontal ligament (P), Cementum apposition (C), Root resorption (R), and Dentin transparency or translucency (T)

Each of these criteria is assigned a score (n) ranging from 0 to 3, as illustrated in Figure 13. The cumulative score (Y) is obtained by summing the scores of individual age changes. Gustafson calculated an estimation error of ±3.6 years for this method in 1947 (Nganvongpanit et al., 2017).



A_0 = no attrition	A_1 = attrition within enamel	A_2 = attrition reaching dentin	A_3 = attrition reaching pulp
S_0 = no secondary dentin	S_1 = secondary dentine has begun to form in upper part of pulp cavity	S_2 = pulp cavity is half filled	S_3 = pulp cavity is nearly or wholly filed with secondary dentin
P_0 = no periodontosis	P_1 = periodontosis just begun	P_2 = periodontosis along first one-third of root	P_3 = periodontosis has passed two-thirds of root
C_0 = normal layer of cementum laid down	C_1 = apposition a little greater than normal	C_2 = great layer of cementum	C_3 = heavy layer of cementum
R_0 = no root resorption visible	R_1 = root resorption only on small isolated spots	R_2 = greater loss of substance	R_3 = great areas of both cementum and dentin affected

Figure: Gustafson's method (1950) point values" – scoring for regressive changes namely: Attrition, secondary dentin, periodontitis, cementum apposition, and root resorption (Verma et al., 2019).

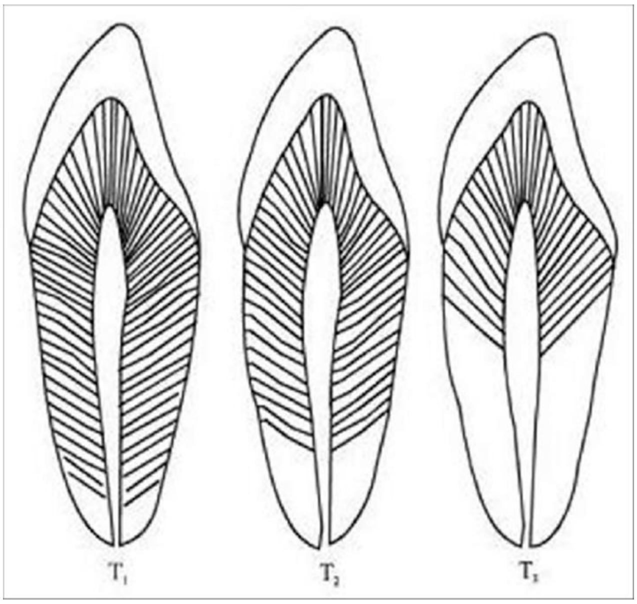


Figure 13: Gustafson's method (1950)" – Scoring for root transparency where T1 = noticeable root transparency, T2 = root transparency extends over the apical third of the root, T3 = root transparency extends over the apical two-thirds of the root.

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The sum of scores for each criterion (*An + Pn + Sn + Cn + Rn + Tn*) equals the total score (Y), where 'n' represents the score for each individual criterion.

There was a direct linear relationship observed between the total score (Y) and age. Age estimation was performed using the equation: *Age = 11.43 + 4.56 × Y (total score).*

Dalitz method (1962)
Dalitz refined Gustafson's approach by implementing a 5-point scoring system ranging from 0 to 4. Criteria for root resorption and secondary cementum were omitted (Nishanth et al., 2020). The remaining four criteria, applied to the 12 anterior teeth, demonstrated a strong correlation with age. However, this method excludes the utilization of posterior teeth. Dalitz suggested utilizing up to four of the 12 anterior teeth per individual. The standard deviation in age estimation using this method is approximately ±6 years. One limitation of the Dalitz method is its exclusion of premolars and molars, which are more likely to be preserved in cases of severe trauma or mass disasters. (Verma et al., 2019)

$E' = 8.691 + 5.146A' + 5.338P' + 1.866S' + 8.411T'$

Bang and Ramm Method (1970)
They found that the root dentine appears to become transparent during the third decade starting at the tip of the root and advancing coronally with age (Nishanth et al., 2020). It was found that, transparency of the root dentin advances coronally from the tip of the root during the third decade. A great advantage of the method is that good results are obtained by measuring intact roots only.

Johanson Method (1971)4
Age changes were differentiated into seven different stages (A0 - A3) and evaluated for the same six criteria, mentioned earlier, attrition (A), secondary dentine formation (S), periodontal attachment loss (P), cement apposition (C), root resorption (R), and apical translucency (T). Johanson made a more detailed study of the root transparency and stated that it is more clear when the thickness of the ground section of the tooth was 0.25 mm. The following formula was recommended:

$$\mathbf{Age = 11.02 + (5.14 \times A) + (2.3 \times S) + (4.14 \times P) + (3.71 \times C) + (5.57 \times R) + (8.98 \times T)}$$

Maple and Rice Technique (1978)
Maples and Rice were the pioneers in reviewing Gustafson's data and reevaluating error estimates. They identified several issues with the statistical analysis of the original data and were unable to validate Gustafson's initial error estimate of ±3.63 years. Their reevaluation yielded an associated error of ±7.03 years, nearly double Gustafson's estimate. Upon recalculating Gustafson's data, Maples and Rice formulated the following equation: Age = 4.26x + 13.45 (with a correlation coefficient r = 0.912), where x represents the total point count. (Phulari & Dave, 2021)

Maples and Rice observed that Gustafson's regression line was derived from a total sample size of 41 teeth, but these data were actually drawn from only 19 unique teeth. Furthermore, it was found that some of these same teeth were utilized to assess the accuracy of the regression line. This practice was deemed a significant limitation, as it does not constitute a valid test of the model's effectiveness

Pollard and Lucy Method
Pollard and Lucy subsequently reexamined both Gustafson's and Maples and Rice's methodologies. They observed discrepancies in Gustafson's linear regression equation, noting that it was constructed using only 8 samples, contrary to the 19 claimed by Maples and Rice. Additionally, they highlighted that both methodologies relied solely on linear regression analysis, which isn't the recommended statistical approach when considering multiple parameters. Consequently, they recalculated the statistics using a multiple regression model, resulting in a revised error estimate of ±15.9 years (Phulari & Dave, 2021).

Solheim Method (1993)
Solheim used five of the changes that Gustafson recommended (attrition, secondary dentin, periodontitis, cementum apposition, and root transparency) and added another three new changes that showed a significant correlation in different types of teeth (Nishanth et al., 2020). The three new age-related changes were surface roughness, color, and sex.

Numerous modifications have been implemented to Gustafson's approach, typically involving the exclusion of certain parameters, particularly periodontal attachment and root resorption. However, the majority of these modifications have not succeeded in producing a more precise error estimate. Amongst the modified methods, the Kashyap and Koteshwar method stands out as highly accurate and consistently reproducible, making it widely regarded as the most accepted approach (Phulari & Dave, 2021).

The limitations of Gustafson's method
It is not applicable for use in living individuals. The scoring relies on subjective interpretation of regressive changes. Conducting multiple assessments renders it a labor-intensive process. Evaluating the periodontal ligament is challenging in decomposed remains. A single regression line was applied universally to all teeth, regardless of their eruption timing or morphological disparities. Equal weight was assigned to all six criteria, neglecting any potential interrelationships between them. Proficiency in dental histological techniques is imperative for proper implementation (Verma et al., 2019).

The Lamendin's Method
Lamendin's method uses a combination of macroscopic and microscopic analyses of teeth to determine the age of an individual. This method is based on the assumption that a tooth progresses through different developmental stages at a predictable rate and that certain features can be observed to determine the stage of development reached by the tooth (Mary et al., 2006). According to Juhasz et al. (2014), the Lamendin's method is widely used in forensic and archaeological studies due to its high accuracy.

The first step in the Lamendin's method is to observe the tooth's macroscopic features, such as the presence of root completion and tooth eruption. The second step is to extract a small section of the tooth's cementum and analyze it microscopically for the presence of annulations (Piyush et al., 2021). These annulations represent lines of incremental growth that can be counted and used to determine the age of the individual. Eisenburger and Addy (2002) note that the Lamendin's method has been validated in several studies and has proved to be a reliable and accurate method of dental age estimation. One advantage of the Lamendin's method is that it does not involve radiation exposure, making it a safer alternative to radiographic methods, such as the Demirjian's method.

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The Lamendin's method involves the evaluation of tooth sections by measuring the attrition of the enamel, the transparency of the root, and the root length. According to Lamendin et al. (1992), this method is based on the assumption that tooth development and wear are related to age, and that teeth in different stages of development wear differently. The Lamendin's method has been found to be reliable and valid in estimating age in both living and deceased individuals (Piyush et al., 2021). According to a study by Olze et al. (2010), the Lamendin's method demonstrated high accuracy in estimating age in a sample of German children and adolescents. The study found that the method's standard error of the estimate ranged from 1.2 to 1.5 years (Gretel et al., 2007). Similarly, a study by Cameriere et al. (2008) found that the Lamendin's method provided accurate age estimates in a sample of Italian children. The study reported a standard error of the estimate of 1.35 years. In a similar study, Egbode et al. (2023) posited that the Lamendin's age estimation method provides an accurate age estimation in a sample of Nigerian population.

AGE ESTIMATION TECHNIQUES IN DIFFERENT AGE GROUPS

Age estimation methods can be considered based on the stage of tooth development in the following:

1. Pre-natal, neonatal and post-natal
2. Children and adolescents
3. Adults

Pre-natal, Neonatal and Post-natal Age Estimation

Radiographically, the mineralization of deciduous incisors starts at the 16th week of intrauterine life. Before the mineralization of tooth germs starts, the tooth germs may be visible as radiolucent areas on the radiograph; the subsequent radiographs of the mandible will depict the deciduous teeth in various stages of mineralization as per the pre-natal age of the fetus **(Priyadarshini et al., 2015).** One of the methods employed is by Kraus and Jordan (1965) who studied the early mineralization in various deciduous teeth as well as the permanent first molar. The development is described in 10 stages, denoted by Roman numerals from I to X; the IXth stage includes three stages and the Xth stage includes five stages **(Priyadarshini et al., 2015).**

The London atlas has also been said to be able to estimate age from as early as 20 weeks in-utero to 23 years of age. Figure 11 depicts the London atlas.

Age Estimation in Children and Adolescents

Dental age estimation in children and adolescents is based on the time of emergence of the tooth in the oral cavity and the tooth calcification. The radiographic analysis of developing dentition, especially when there is no clinical evidence available (2.5-6 years) as well as the clinical tooth emergence in various phases will help in age determination (Priyadarshini et al., 2015; Ubelaker and Khosrowshahi, 2019)

Methods applied for age determination in children and adolescents

In estimation of age in this age group using the teeth, the following methods as previously described have been found to be very useful and accurate; Schour and Masseler method (1941), Nolla's method (1960), Moorees, Fanning and Hunt method, Ubelaker's chart, Cameriere method. London atlas, Demirjian method, and the WITS atlas. Methods such as Ikeda, Kvaal, Havvikko as well as Lamendin have not been proven to be very reliable in this age group.

Age Estimation in Adults

Clinically, the development of permanent dentition completes with the eruption of the third molar at the age of 17-21 years, after which the radiographic age estimation becomes difficult. The two methods commonly followed are the assessment of the volume of teeth and the development of the third molar. Volume assessment of teeth, Pulp-to-tooth ratio method by Kvaal, Coronal pulp cavity index, Development of third molar, Harris and Nortje method and Van Heerden system are some of the techniques that have been used with moderate to excellent accuracy in adult population.

Volume assessment of teeth

The age estimation in adults can be achieved by radiological determination of the reduction in size of the pulp cavity resulting from a secondary dentine deposition, which is proportional to the age of the individual **(Priyadarshini et al., 2015).**

Pulp-to-tooth ratio method by Kvaal

In this method, pulp-tooth ratio is calculated for six mandibular and maxillary teeth, such as maxillary central and lateral incisors; maxillary second premolars; mandibular lateral incisor; mandibular canine; and the first premolar. The age is derived by using these pulp to tooth ratios in the formula for age determination given by Kvaal et al.

$$Age = 129.8 - (316.4 \times m)\ (6.8 \times [W\text{-}L])$$

The Coronal Pulp Cavity Index

This method calculates the correlation between the reduction of the coronal pulp cavity and the chronological age. Only mandibular premolars and molars were considered, as the mandibular teeth are more visible than the maxillary ones. Panoramic radiography is used to measure the length (mm) of the tooth crown (coronal length, [CL]) and the length (mm) of the coronal pulp cavity (coronal pulp cavity height or length [CPCH]). The tooth-coronal index (TCI) is computed for each tooth and regressed on the real age of the sample using the formula (Ikeda et al.,1985).

$$TCI = CPCH / CL * 100$$

Development of third molar

The radiographic age estimation becomes problematic after 17 years of age as eruption of permanent dentition completes by that age with the eruption of the third molar. Later, the development of the third molar may be taken as a guide to determine the age of the individual.

Harris and Nortje method

The Harris and Nortje method, developed in 1984, is a technique used for estimating age based on the analysis of the mandibular third molar (wisdom tooth) development (Harris & Noortje, 1984). The method specifically examines the developmental stages of the mandibular third molar, which is one of the last teeth to develop and erupt. The third molar's development continues into late adolescence and early adulthood, making it a useful indicator for age estimation in this age group. Harris and Nortje identified and classified various stages (0 to 10) of third molar development, from initial formation to full eruption. These stages are assessed using radiographic images (X-rays) of the lower jaw (Acharya, 2011).

Van Heerden system

Similar to other dental age estimation methods, the Van Heerden system categorizes the development of the third molar into specific

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stages (Van Heerden & Pharoah, 1987). These stages include the formation of the crown, the development of the roots, and the closure of the root apices. The method relies on radiographic (X-ray) images of the third molar to assess its developmental stage. This non-invasive approach allows for accurate observation of the internal structure and growth of the tooth (Acharya, 2011). By comparing the observed developmental stage of the third molar with standardized stages outlined in the Van Heerden system, the age of an individual can be estimated. This is particularly useful in forensic cases and legal scenarios where age determination is required.

RECENT ADVANCES IN DENTAL AGE ESTIMATION

Recent advances in dental age estimation have been driven by technological innovations and the integration of multidisciplinary approaches. These advancements can be broadly categorized into digital imaging and radiographic techniques, biochemical methods, and computational and machine learning models.

Digital Imaging and Radiographic Techniques

Digital imaging technologies, such as cone-beam computed tomography (CBCT) and 3D dental imaging, have revolutionized dental age estimation. These methods provide high-resolution images that allow for precise measurement of dental structures.

Cone-Beam Computed Tomography (CBCT)

CBCT offers three-dimensional imaging of dental and maxillofacial structures, providing detailed views of tooth development and root morphology. This technology enhances the accuracy of dental age estimation, particularly in cases where traditional two-dimensional radiographs may be insufficient (Franklin and Cardoso, 2019).

3D Dental Imaging

Three-dimensional dental imaging, including 3D surface scanning and stereophotogrammetry, allows for the creation of detailed digital models of teeth. These models can be analyzed to assess developmental stages and wear patterns more accurately than traditional methods (Franklin and Cardoso, 2019).

Radiocarbon Dating

Radiocarbon dating of dental enamel has been used to estimate the age of individuals based on the incorporation of carbon isotopes during tooth formation. This method can provide precise age estimates for individuals who were alive during periods of known atmospheric carbon fluctuations, such as those caused by nuclear testing in the mid-20th century (Spalding et al., 2005).

Computational and Machine Learning Models

The integration of computational models and machine learning techniques has significantly enhanced the accuracy and efficiency of dental age estimation.

Machine Learning Algorithms

Machine learning algorithms, including neural networks and support vector machines, have been trained on large datasets of dental images and radiographs. These models can identify patterns and correlations that may not be apparent through traditional analysis, leading to more accurate age estimates (Lee & Lin, 2020).

Artificial Intelligence (AI) and Deep Learning

Deep learning, a subset of AI, involves training neural networks with multiple layers on extensive datasets. This approach has shown promise in automating the assessment of dental maturity and predicting age with high accuracy. Deep learning models can analyze complex features of dental structures, such as root development and pulp chamber morphology, that are difficult to quantify manually (Lee & Lin, 2020).

Applications of Advanced Dental Age Estimation Techniques

The advancements in dental age estimation have wide-ranging applications in forensic science, clinical practice, and legal contexts. In forensic science, accurate age estimation is crucial for identifying unknown human remains, especially in cases of mass disasters, war crimes, and unmarked graves. The integration of advanced imaging and biochemical techniques has improved the reliability of forensic age assessments, aiding in the identification process (Schmeling & Olze, 2015). In clinical practice, dental age estimation is used to monitor the development of children and adolescents, diagnose growth disorders, and plan orthodontic treatment. The use of digital imaging and machine learning models allows for more precise tracking of dental development, leading to better-informed clinical decisions (Scheurer & Delémont, 2018).

In legal contexts, dental age estimation is often required for age determination in immigration and asylum cases, as well as in the assessment of criminal responsibility for juvenile offenders. The enhanced accuracy of advanced techniques provides more reliable evidence for legal proceedings, ensuring fair and just outcomes (Schmeling & Olze, 2015).

FUTURE DIRECTIONS

The future of dental age estimation lies in the continued integration of emerging technologies and interdisciplinary research. Several areas hold promise for further advancement:

Genomic and Epigenomic Analysis

The analysis of genomic and epigenomic markers in dental tissues may provide additional insights into age estimation. Research into the genetic and epigenetic regulation of tooth development could lead to new biomarkers for age assessment (Ritz-Timme & Cattaneo, 2018).

Integration of Multimodal Data

Combining data from multiple sources, such as dental imaging, biochemical analysis, and genomic information, may enhance the accuracy and robustness of age estimates. Multimodal approaches can provide a more comprehensive understanding of dental development and aging (Franklin & Cardoso, 2019).

Continuous Learning and Adaptation

The use of continuous learning models in machine learning can allow for the ongoing improvement of age estimation techniques. As new data becomes available, models can be updated and refined to maintain and enhance their accuracy (Lee & Lin, 2020).

CONCLUSION

Determination of dental age is done by reference to the ever-growing human deciduous and permanent dentitions. Radiographic evaluation, morphological assessment and biochemical analysis play significant role in dental age estimation. Recent advances in dental age estimation have significantly improved the accuracy and reliability of this important field. The integration of digital imaging, biochemical methods, and machine learning models has transformed traditional approaches, offering new possibilities for forensic science, clinical practice, and legal applications. However, these advancements also raise ethical considerations and challenges that must be addressed to ensure their responsible and

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equitable use. The future of dental age estimation lies in the continued exploration of emerging technologies and interdisciplinary collaboration, paving the way for even more precise and comprehensive age assessment techniques.

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