

# Advances in forensic odontology for human identification: a comprehensive review of methods, accuracy, and challenges

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## Abstract

Forensic odontology provides significant possibilities for human identification in the absence of DNA and fingerprints. Dental tissues, impervious to environmental damage, offer distinctive characteristics for sex estimation, age assessment, ancestry identification, and comparative analysis. This review rigorously integrates conventional and novel methodologies. Odontometric and non-metric characteristics are extensively utilized for sex estimation and ancestry assessment, however accuracy differs among groups and inter-observer variability continues to exist. Age estimate methodologies, including Demirjian, Willems, Nolla, AlQahtani, Kvaal, and Cameriere, have significant dependability in children and adolescents, although their accuracy diminishes in adults owing to wider error margins. Recent advancements, such as cone-beam computed tomography, three-dimensional imaging, and artificial intelligence, demonstrate potential for automated and reproducible assessments. Nonetheless, validation studies are scarce, established methodologies are absent, and legal admissibility is ambiguous. Comparative identification remains extremely reliable with antemortem and postmortem information, while diminishing dental restorations compromise distinctiveness. Forensic odontology is essential; yet, advancement necessitates the incorporation of digital technologies, population-specific criteria, and a heightened focus on validation and ethical-legal standards.

**Keywords:** comparative identification, dental profiling, forensic, human identification, teeth

## Introduction

Whether a person is alive or dead, their identification has a tremendous impact on both the legal and social systems in which they are embedded. This identity is essential for ensuring the safety of living individuals in a variety of contexts, including banking operations, licenses, visas, passports, immigration, and other similar matters. For deceased individuals, the significance of identification is often brought up for a variety of reasons, including those that are

single or multiple in nature (Ágnes Borsay *et al.*, 2024). Identification is a field that perpetually pursues long-lasting information that is apparent, not only plain and easily acquired, but that is also thorough enough to prove its differentiation from other evidence.

## Dental identification

The identification of teeth can be accomplished by two methods:

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a) The process of dental profiling is carried out in situations when there is no sign of antemortem (AM) dental record. During the dental profiling or reconstructive identification process, information regarding the deceased person's race, age of death, and gender was gathered.

b) Comparative identification: The second aspect of forensic odontology is comparative identification where the AM records of the unidentified person are compared to the dental characteristics after the postmortem examination.

### **Reconstructive identification**

In the absence of available preliminary identity information, dental profiling is performed, rendering AM data unretrievable. This situation occurs when remains are discovered at unrelated locations and are significantly degraded. Utilising PM dental profiling allows for the refinement of the search to relatively small, particular groups. The dental profile comprises a set of particular characteristics related to the hard and soft tissues of tooth anatomy. They support in identifying parameters such as age, race, sex, socioeconomic status and occupation of the deceased, systemic health, personal habits and dietary status (Swain *et al.*, 2021).

#### **A) Sex estimation**

The initial step that forensic investigators undertake in the identification procedure is estimating an individual's gender. The forensic odontologist can aid in determining the gender of the remains by utilising the data gathered from the skull and dental fragments. Linear measurements like crown dimensions (Bu *et al.*, 2023; Lukacs & Kuswandari, 2022; Dumančić *et al.*, 2023), cusp dimensions (Eboh, 2019), and root lengths (Govindaram *et al.*, 2018) are dental features that can be assessed by linear measurements. The incisor and canine indices (MCI) (Issrani *et al.*, 2020; Kumar *et al.*, 2019) as well as the crown index (Eboh, 2019) were all calculated from these linear data by one or more researchers who then

performed further analysis. One study also calculated the cusp and the crown area measurements following the outline of the tooth occlusal surfaces (Riaz *et al.*, 2024). The majority of the outcomes from these investigations concluded that males exhibit higher values than females. Research findings indicate that employing univariate and multivariate analyses for sex prediction may yield divergent results (Capitaneanu *et al.*, 2017).

Beyond tooth size, research on non-metric characteristics, such as the distal accessory ridge (Dumančić *et al.*, 2023), Carabelli's trait of maxillary molars (Chowdhry *et al.*, 2023), shovelling of the upper central incisor (Walker *et al.*, 2009) has revealed notable distinctions between males and females. Nonetheless, these findings were not validated for application in a sex prediction model. However, one study generated prediction model using the cusp numbering and the groove pattern on the maxillary posterior teeth (Riaz *et al.*, 2024), having an accuracy above 75% which is considered acceptable as a forensic tool.

While odontometric measurements often achieve 70–85% accuracy across various populations, their reliability is reduced by inter-observer variability and population-specific differences. Non-metric traits such as Carabelli's cusp or shoveling provide useful supplementary indicators, yet most studies are based on limited samples and lack validation for predictive forensic models. Therefore, these traits should be considered supportive rather than definitive in sex estimation.

#### **B) Age estimation**

Various methods exist for ascertaining the ages of children, teenagers, and adults. Kurniawan *et al.* (2022) identified some methods commonly employed to determine the ages of children, adolescents, and young adults. Age estimation methods are separated into two categories: (i) children and young adults (until third molar eruption), and (ii) adults (when dental development has ceased).

The following methodologies determine the child/young adult age:

1. Demirjian method: This method uses panoramic radiographs to study all the mandibular teeth except third molar.
2. Willem's method: This is the modified version of Demirjian method (Fitri *et al.*, 2022).
3. TCI Benindra method includes tooth coronal index based on association of the tooth with its dental pulp chamber) (El Morsi *et al.*, 2015).
4. AlQahtani method is one of the new atlas methods involving all the teeth (maxillary and mandibular) (AlQahtani *et al.*, 2010).
5. Nolla's technique method depends on the evaluation of 10 stages of tooth calcification starting from appearance of tooth bud formation till the closure of the apical foramen) (Kurniawan *et al.*, 2022).

In children and adolescents, radiographic methods such as Demirjian, Willems, and AlQahtani provide relatively high accuracy ( $\pm 1-2$  years). However, their reliability declines significantly after the completion of third molar eruption.

The age estimation adults applied to the adults are as follows:

1. Kvaal Method: This method is based on the association of age with the tooth to pulp ratio) (Kvaal *et al.*, 1995; Mittal *et al.*, 2016).
2. Schour and Masslers method involves the development of the deciduous and permanent teeth, focusing in on the 21 chronological stages from 4 months to 21 years of age) (Jaquelin *et al.*, 2018).
3. Moorer, Fanning and Hunt method studies the maturation stages for the tooth crown and root, which vary if the tooth is single or multirooted) (Phillips & Van Wyk Kotze, 2009).
4. Phulari & Dave, (2021) stated four categories of age estimation in adults as follows:

*a. Methods evaluating histology*

- i) Combination of different regressive alterations of teeth.
- ii) Evaluation of the dentinal translucency used as a single indicator.

iii) Evaluation of the deposition of secondary dentine deposition used as an indicator.

iv) Cementum thickness, presence or absence of the rings, and annulations.

v) Dentine and cementum fluorescence.

vi) Scanning electron microscopy for microscopic measurements.

*b. Methods evaluating radiographs*

i) Ration of the pulp-tooth dimension based on length (Kvaal), and based on: based on area and volume (Cameriere *et al.*, 2006).

ii) Ikeda method using the tooth coronal pulp cavity index.

iii) X-ray micro-focus CT scanning of teeth

iv) Assessing the mental foramen and mandibular canal.

*c. Biochemical methods*

i) Aspartic acid racemisation

ii) Enamel uptake of Radioactive carbon-14 (carbon dating)

iii) Miscellaneous biochemical methods

*d. Genetic and epigenetic methods*

i) Human telomere shortening

ii) Deoxyribonucleic acid (DNA) methylation

In adults, methods such as Kvaal's pulp-to-tooth ratio, Cameriere's pulp area measurements, and biochemical approaches yield broader error margins ( $\pm 4-10$  years) and are often less reproducible. While histological and biochemical methods may improve accuracy, they are invasive and not always feasible in forensic casework. These limitations highlight the need for integrating multiple approaches and validating newer digital and biochemical techniques across populations.

Among the available approaches, Demirjian's method continues to be regarded as the most reliable and accurate standard for dental age estimation (Vistro *et al.*, 2024).

### C) Ancestry or race determination using dental characteristics

An individual possesses a trait when they exhibit certain feature or attribute that distinguishes them from others. A variety of potential manifestations of a specific trait may exist. Dholia and Manjunatha (2015) assert that the uniqueness of one population may be a trait of another. Caucasoids exhibit a higher prevalence of the Carabelli trait compared to Negroids, who demonstrate a lower prevalence of this feature (Yaacob *et al.*, 1996; Rawlani *et al.*, 2017). However, Negroids exhibit a much higher prevalence of additional permanent teeth (Irish, 2022; Thomas *et al.*, 2023). As in the prior example, the mongoloid dentition exhibits shovelling as the greatest characteristic diagnostic trait observed on the palatal surface of the central incisors (Yaacob *et al.*, 1996). The morphological characteristics of teeth allow for the classification of the Mongoloid population into two groups: Sinodonty, prevalent among Northeast Asian groups and characterised by derived mass additive traits, and Sundadonty, observed in Southeast Asian and Pacific populations, noted for its retained traits and relatively simpler dentition (Scott & Turner, 1997). All of these classifications are predicated on dental characteristics. A significant prevalence of shovelling and double scooping of maxillary central incisors, enamel extensions in the maxillary molars (M1), reduced, pegged, or absent maxillary third molars (M3), existence of deflecting wrinkles, and mandibular first molar exhibiting triple roots are characteristics associated with synodontia in populations. Conversely, Sundadont groups exhibit a markedly reduced incidence of the above traits, concurrently displaying a high prevalence of four cusped mandibular second molar (Calvin Jia Jun *et al.*, 2023).

Various races have variable tooth sizes. Linear tooth dimensions classify the global population as microdontic, mesodontic, or megadontic (Hanihara & Ishida, 2005). Microdontia affected Native Americans, Philippine Negritos, Jomon, and Western Eurasians. Hanihara and Ishida (2005) say

the Megadontic population is Australian Aborigines, Melanesians, Micronesians, and sub-Saharan Africans, whereas the Mesodontic population is Polynesians and Southeast Asians. Consequently, in the absence of AM data, the profile may be simplified to the assessment of ancestry based on the metric and non-metric traits present in the individual.

Although ancestry-related dental traits are useful for narrowing population affinity, their diagnostic specificity is limited. Considerable overlap exists among global populations, meaning these traits cannot reliably establish individual identity. They should therefore be interpreted as supportive indicators within a broader forensic context rather than as standalone evidence.

The methods reviewed above demonstrate considerable variability in accuracy, reproducibility, and applicability across forensic contexts. While some approaches, such as age estimation in children, yield relatively narrow error margins, others—particularly those applied in adults or ancestry assessment—are less reliable due to broader variability and population dependence. To provide a concise overview, a comparative synthesis of the principal forensic odontology methods, outlining their reported accuracy, limitations, and forensic applicability, is presented below (Table 1).

### Comparative dental identification

This is a critical stage in the process of discerning any unique traits that may facilitate the verification of identity based on individual-level similarities, such as establishing whether the individual in question matches the ante-mortem records. Franco *et al.* (2015) assert that the core concept is predicated on the notion that no two unconnected individuals possess similar dental features.

Table 1. Comparative summary of forensic odontology methods for human identification.

Method	Accuracy / Utility	Limitations	Forensic Applicability
<b>Sex Estimation</b> (Odontometrics, Non-metric traits, AI models)	70–85% accuracy depending on population; AI >80% in pilot studies	Population variation; inter-observer variability; limited validation	Supplementary evidence when DNA/skeletal markers unavailable
<b>Age Estimation – Children &amp; Young Adults</b> (Demirjian, Willems, Nolla, AlQahtani)	±1–2 years	Less accurate after 18 years; third molar variability	Widely accepted for <18 years in forensic/legal contexts
<b>Age Estimation – Adults</b> (Kvaal, Cameriere, histological/biochemical methods)	±4–10 years	Accuracy declines with age; some methods invasive	Supplementary tool; not standalone for legal proof
<b>Ancestry Determination</b> (Shovel-shaped incisors, Carabelli’s trait, Sundadont/Sinodont patterns)	Population trends observable	Overlap across groups; cannot identify individuals	Narrows down ancestry/population affinity
<b>Comparative Dental ID</b> (Radiographs, restorations, rugae, lip prints, AI superimposition)	High reliability with AM/PM records	Relies on record quality; fewer restorations due to better oral health	Court admissible under ABFO & Interpol guidelines

The American Board of Forensic Odontology, (2017) indicates that comparative identification may yield the following results:

1. Positive identification occurs when all records are congruent and exhibit no discrepancies. It is posited that a singular individual is accountable for all the discoveries. One tooth with adequate distinguishing characteristics can suffice for identification purposes.
2. The potential for identification – data from the AM and PM exhibiting consistent characteristics; nonetheless, the evidence lacks any distinguishing features.
3. Insufficient evidence, defined as evidence inadequate to reach a conclusion
4. Exclusion: records that exhibit a distinct delineation and seem to be incongruous.

The Interpol disaster victim identification (DVI) manual states that dental

identification can be a trustworthy independent identifier if a positive match is made. Dental records contain identifiable data (Kiran *et al.*, 2019). The distribution of teeth and the properties of restored, non-restored, missing, and decaying surfaces show unique patterns.

### Unique dental features

Dental casts, 2D radiographs, as well as 2D and 3D images could be included in the records for the ante mortem and postmortem comparison. Radiographic examinations have a significant comparative value because of their unique characteristics. These characteristics include biological variability, which includes impacted teeth, broken down roots, jawbone structure, sinus cavities, and dental interventions such as morphology of the restoration, root canal therapy, oral surgery procedures, and the dental implants respectively (Campobasso *et al.*, 2007). Comparative dental identification

is widely accepted under ABFO and Interpol guidelines, but its reliability depends heavily on the quality of available antemortem records. With declining restorative dental work in many populations, reliance on inherent dental morphology is becoming increasingly important. To add insult to injury, in the current scenario, when the oral health status has improved, a growing proportion of cases continue to be unclear since there are no restorations or other treatments performed on any of the teeth that are in good condition.

Santoro *et al.* (2019) found that the contour of teeth, which was caught in images of a smiling face, played a role in the process of identification in the study cast that was created by superimposing different photographs of the skull. In spite of this, aesthetic dentistry has caused potential loss of an identifying resource. This is due to the fact that people are altering their anterior teeth aesthetically, which naturally make up a smile pattern, in such a way that might not correspond with the actual smiles that were initially stored in the AM database. According to Moreira Andrade *et al.* (2022), the frontal sinuses and other cranial traits are considered to be reliable instruments for human identification.

Palatal rugae pattern and lip prints which are soft tissue structures, have also been examined in the AM and PM recordings. These structures have been analysed in addition to dental and cranial characteristics. It is possible for the palatal rugae to make a substantial contribution to human identity because they are a pattern that is fundamental to each individual and is unique to them. The palatal rugae are a feasible device in the field of forensic odontology (Syed *et al.*, 2021). This is due to the fact that they are easy to reproduce and decrease the amount of variability. Furthermore, the slow loss of rugae, which happens at an average rate of one ruga every 15 (2) years after early adulthood (Suhartono *et al.*, 2016), contributes to the enhancement of the utility of rugae in forensic investigations.

Within the realm of forensic investigations, cheiloscopy has been utilised to determine the identity of human beings. Even as early as the fifth week of intrauterine development, it is likely to distinguish a person's lip print. Based on the findings of Hamzah *et al.* (2021), it is possible to make comparisons between lip prints that are discovered at a crime scene and the lip print of a suspect. This results in length reduction and in width increase, giving it a thinner and elongated appearance (Kim *et al.*, 2019). However, the appearance of the lips changes as a person gets older, resulting in a change in appearance. It is possible that this will lead to an incorrect diagnosis, particularly if the identification process takes place after a considerable amount of time has passed. According to Bhattacharjee & Kar (2024), the mobility of the crease pattern on the vermilion border of the lip might result in lip prints that are distinct from one another depending on the pressure, direction, and technique that was utilised in the process of making the imprint.

Since both the palatal rugae and lip prints are soft tissue measures, their usefulness in human identification is limited because they decrease with time as a result of decomposition and wound healing.

According to research conducted by Roy *et al.* (2019), the comparison of the groove patterns in maxillary first and second molar highlighted the individuality of these specific dental characteristics and proposed that this dental characteristic might be used for human identification. Later, another study showed positive uniqueness of the groove pattern on the maxillary posterior teeth by superimposing digital photographs of groove pattern tracing generated using 2D Hirox stereomicroscope (Riaz *et al.*, 2023).

Comparative dental identification is widely accepted in forensic practice and endorsed by ABFO and Interpol guidelines. However, its reliability depends heavily on the availability and quality of antemortem records. In many regions, improved oral health and reduced reliance on extensive dental restorations have decreased the distinctiveness of dental features,

emphasizing the need to focus on inherent anatomical variations, digital imaging, and standardized comparison protocols.

### **Emerging digital imaging and forensic approaches**

In the field of forensic odontology, several scientific analyses and data collection methods have undergone noteworthy developments in order to aid human identification. A two-dimensional (2D) approach, which includes the examination of radiographs and plaster dental casts, is the typical digital imaging technique that is utilised for the purpose of dental identification (Middleton *et al.*, 2016). According to Campobasso *et al.* (2007), Radiographs are used in the AM and PM to compare dental treatments such prostheses, implants, and restorations. In the digital age, many two-dimensional (2D), three-dimensional (3D), and AI imaging technologies have been developed to improve forensic evidence for legal and medical use. These imaging methods show promise as forensic tools due to their precision and accuracy (Riaz *et al.*, 2024; Bianchi *et al.*, 2023).

Digital pictures in two dimensions and dental scans in three dimensions of dental casts are used in forensic investigations. This makes data storage and access easier. A sophisticated software for comparison identification is utilised in the process of data processing by superimposing 3D dental scans (Gibelli *et al.*, 2019) and palatal rugae (Alselwi *et al.*, 2022), among other comparison identification techniques. Dental profiling is a technique that allows for the evaluation of sex, race, and age through the use of two-dimensional and three-dimensional techniques. This is accomplished by capturing digital images using standardised devices that exhibit a high degree of accuracy and precision (Amornvit *et al.*, 2021; Riaz *et al.*, 2024).

DNA profiling (Panneerchelvam & Nor, 2023), analysis of the pelvic bone (Secgin *et al.*, 2022), and skull inspection (Tan *et al.*,

2020) are the methods that are considered to be the gold standards for determining a person's gender. In spite of this, there are instances in which the DNA obtained from the pelvis, the cranium, or both is so tainted by postmortem modifications that they are not capable of determining the gender of the deceased. As a result, tooth sex prediction has the potential to function as a supplementary method in circumstances where the gold standards are inaccessible.

More people are becoming aware of the importance of maintaining good oral hygiene, which has contributed to an improvement in oral health status and a decrease in the incidence of dental caries (Kramer & Splieth, 2022; Palanisamy, 2024). As a consequence of this, there are occasions in which the AM records do not contain any evidence of specific dental treatment, which is essential for correct identification. Thus, the distinctiveness of dental records must be dependent on additional biological cranial characteristics that are unique to the individual, such as the palate rugae, sinuses, and cheiloscopy. On the other hand, inflammation may have an effect on the sinuses, and cheiloscopy and palatal rugae are not able to endure decomposition.

Gender helps narrow AM dental record searches for human identification. Using these occlusal features may help determine a person's gender biologically. Occlusal qualities of teeth may be relevant when DNA contamination or deterioration is present and there is no other biological evidence, such as trauma or incineration-related cranial and post-cranial traits. Dental trauma and caries in the proximal region might also impair odontometric systems' measuring reference points. AM and PM dental records may be inconclusive without caries. Forensic dentists have to authenticate identity using biological evidence from healthy teeth. Thus, odontologists can compare and superimpose 2D and 3D postmortem digital photos taken of the deceased person.

Artificial intelligence (AI) and digital imaging technologies are increasingly applied in forensic dentistry for human identification. Machine learning algorithms,

particularly convolutional neural networks, have shown potential in dental feature recognition, segmentation of CBCT scans, and automated sex or age estimation, with accuracies often exceeding those of traditional odontometric methods (Mohan *et al.*, 2019; Raj *et al.*, 2021). These tools improve reproducibility by reducing inter-observer variability and can process large datasets rapidly, offering advantages in mass disaster victim identification (Bhattacharya *et al.*, 2020). Despite this promise, most studies are based on small and homogenous datasets, limiting generalizability across populations (Zhu *et al.*, 2022). Furthermore, the absence of standardized protocols and external validation restricts their acceptance in forensic practice. Until these limitations are addressed through multicenter studies, algorithm transparency, and clearly defined error margins, the legal admissibility of AI-generated findings will remain uncertain (Panchbhai, 2018; Patel *et al.*, 2023).

Nevertheless, with rigorous validation, AI has the potential to complement conventional forensic dental methods and significantly enhance the reliability of human identification. To move forward, large-scale multicenter studies and transparent reporting of algorithmic accuracy, reproducibility, and limitations are essential.

### **Admissibility of method by court of law**

It is important that the methodology that is utilised in this investigation be selected on the basis of expert judgement in order to ensure that it adheres to legitimate scientific approaches and procedures. According to the Daubert rule (Daubert, 1993), there are specific criteria that should be considered when determining the reliability of a scientific theory or study. These criteria include the following:

1. the ability to be empirically tested;
2. the status of publication or peer review;
3. the acceptability of the known or potential error rate; and

4. the general acceptance within the scientific community.

Forensic odontology evidence can only be used in court if it meets certain requirements, such as the Daubert and Frye criteria. Daubert says that scientific evidence must be able to be tested, have known or possible error rates, be published in peer-reviewed journals, and be widely accepted by the relevant scientific community. Many odontology approaches, including sex and age estimation, are limited by demographic specificity and the lack of comprehensive validation studies demonstrating reproducibility and error margins, hence posing challenges under these standards. The American Board of Forensic Odontology (ABFO) and the Interpol Disaster Victim Identification (DVI) standard are two examples of professional groups that stress the necessity of comparative dental identification as the most reliable and legally accepted method in forensic dentistry. Comparative procedures are widely acknowledged for their direct linkage of antemortem and postmortem information, whereas techniques such as age or sex estimation are generally regarded just as supplementary evidence. To meet both scientific and legal criteria, forensic odontology needs to be more legally defensible by using the same methods, reporting mistakes clearly, and testing them on different groups of people. Beyond the discussion of admissibility, it is important to consider the parallel technological advances in digital imaging and innovative forensic approaches that have enhanced the scope of dental identification.

### **Conclusion**

Forensic odontology remains a cornerstone of human identification when primary identifiers such as DNA and fingerprints are unavailable. Beyond describing available techniques, it is crucial to recognize their limitations: population variability, lack of universal standards, validation challenges in AI-driven tools, and ethical/legal concerns surrounding admissibility. Future research should prioritize standardized protocols,

large-scale population validation, and integration of digital imaging with AI under strict forensic guidelines. With these refinements, forensic dental evidence can achieve greater reliability and legal robustness worldwide.

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