Review Article

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ADVANCING FORENSIC ODONTOLOGY: UTILIZING INTRAORAL SCANNERS FOR AGE AND SEX DETERMINATION.

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ABSTRAK
Latar Belakang: Odontologi forensik memainkan peran penting dalam identifikasi manusia, terutama dalam memperkirakan usia dan menentukan jenis kelamin. Metode tradisional seperti pencitraan radiografi dan cetakan gigi telah banyak diterapkan, namun metode tersebut memiliki keterbatasan dalam hal presisi, konsistensi, dan kepraktisan dalam skenario forensik yang kompleks. Perkembangan pesat kedokteran gigi digital telah memperkenalkan pemindai intraoral (IOS) sebagai alternatif yang menjanjikan, yang mampu menghasilkan data gigi 3D yang sangat akurat. **Tujuan:** Tinjauan ini bertujuan untuk mengeksplorasi kontribusi pemindai intraoral terhadap odontologi forensik, dengan penekanan pada penggunaannya dalam estimasi usia dan jenis kelamin. **Metode:** Tinjauan naratif dilakukan dengan mencari publikasi di PubMed, Scopus, dan ScienceDirect dari tahun 2016 hingga 2024. Kata kunci yang digunakan meliputi "pemindai intraoral," "cetakan digital," "odontologi forensik," "estimasi usia," dan "penentuan jenis kelamin." **Hasil:** Pemindai intraoral dapat memberikan representasi digital yang tepat dan konsisten dari anatomi gigi dan langit-langit mulut. Penggunaan forensik yang dilaporkan meliputi analisis dimorfisme seksual pada lipatan langit-langit mulut dan bentuk lengkung gigi, serta identifikasi indikator terkait usia seperti pola erupsi dan keausan oklusal. Keunggulan utama meliputi peningkatan akurasi, perekaman non-invasif, dan pengarsipan digital jangka panjang yang andal. Namun, keterbatasan tetap ada, termasuk ukuran sampel yang terbatas, perbedaan antar sistem pemindai, dan tidak adanya pedoman forensik yang terpadu. **Kesimpulan:** Pemindai intraoral menunjukkan potensi yang cukup besar untuk mendukung estimasi usia dan jenis kelamin dalam odontologi forensik. Bukti saat ini menunjukkan bahwa pemindai intraoral dapat meningkatkan presisi dan konsistensi relatif terhadap teknik tradisional, namun studi yang lebih luas dan prosedur standar diperlukan untuk memperkuat penerapannya dalam forensik.
Kata Kunci: Odontologi forensik; Pemindai intraoral; Estimasi usia; Penentuan jenis kelamin; Kedokteran gigi digital

ABSTRACT
Backgrounds: *Forensic odontology plays a crucial role in human identification, especially in estimating age and determining gender. Traditional methods such as radiographic imaging and dental casts have been widely applied, yet they present limitations regarding precision, consistency, and practicality in complex forensic scenarios. The rapid development of digital dentistry has introduced intraoral scanners (IOS) as a promising alternative, capable of generating highly accurate three-dimensional dental datasets.* ***Objectives:*** *This review aims to explore the contribution of intraoral scanners to forensic odontology, with emphasis on their use in age and gender estimation.* ***Methods:*** *A narrative review was performed by searching PubMed, Scopus, and ScienceDirect for publications from 2016 to 2024. Keywords included "intraoral scanner," "digital impression," "forensic odontology," "age estimation," and "sex determination.".* ***Results:*** *Findings from the literature indicate that intraoral scanners can deliver precise and consistent digital representations of dental and palatal anatomy. Reported forensic uses include analyzing sexual dimorphism in palatal rugae and dental arch forms, along with identifying age-related indicators such as eruption patterns and occlusal wear. Key advantages compared with conventional approaches include enhanced accuracy, non-invasive recording, and reliable*

long-term digital archiving. However, limitations persist, including restricted sample sizes, differences among scanner systems, and the absence of unified forensic guidelines. ***Conclusions:*** *Intraoral scanners show considerable promise for supporting age and gender estimation in forensic odontology. Current evidence suggests they may improve precision and consistency relative to traditional* techniques, yet broader studies and standardized procedures are required to solidify their forensic applicability.

Keywords: Forensic odontology; Intraoral scanner; Age estimation; Sex determination; Digital dentistry.
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Introduction

Forensic odontology supports the identification process by offering estimates of age and sex when other biological clues cannot be used or have deteriorated. In major incidents as well as in everyday forensic work, dependable information from the teeth helps investigators form an early understanding of who the person may be and leads them closer to the correct identity.[1] Over the past decade, advances in digital imaging and artificial intelligence have begun to reshape how dental data are collected, curated, and interpreted for forensic purposes, opening opportunities to improve accuracy, speed, and transparency in age and sex estimation.[2] Advances in digital dentistry have introduced new options to overcome these challenges. One development that has gained particular interest is the intraoral scanner, which can record detailed three dimensional images of the teeth and surrounding oral structures. Although originally created for restorative and orthodontic treatments, these scanners are increasingly valued in forensic applications. They produce precise digital records that can be stored, accessed, and compared with ease, making them especially useful in forensic settings where consistency and traceability are essential.[3] Intraoral scanners perform with high precision, with deviations measured in micrometres. Their reliability has been confirmed in both laboratory and clinical settings, although factors such as arch length, scanning strategy, and the presence of fluids may influence results. These findings indicate that intraoral scanners can serve as dependable tools for producing digital impressions suitable for detailed forensic analysis.[4]

The use of intraoral scanners in forensic odontology continues to broaden. Digital dental models can be compared with antemortem records to support identification, and more recent work shows that these scanners can also assist in bitemark evaluation and in recording postmortem findings that can be directly matched with digital or radiologic data. Researchers have examined palatal morphology and rugae patterns as well, demonstrating that three dimensional digital models are capable of preserving distinctive anatomical traits that help define individual identity. Together, these advances illustrate how intraoral scanners offer flexible applications that enrich the information obtained from radiographs and traditional dental impressions.[5] Artificial intelligence is increasingly influencing how forensic dentistry is practiced. Deep learning systems used on panoramic radiographs have produced encouraging outcomes in estimating age and sex. By automating the process of identifying features and assigning classifications, these technologies help minimize human error and improve the speed of analysis. A number of studies have introduced solid models that combine tooth detection with regression or classification techniques to predict biological traits. Even so, much of this research has relied on two dimensional radiographs, with far less attention given to the possibilities offered by three dimensional intraoral scan data.[6]

The integration of intraoral scanners with artificial intelligence represents a logical step forward. Three dimensional scans capture rich morphological details of teeth, occlusal surfaces, and arch form, which could provide additional markers for age and sex estimation. Emerging computational approaches suggest that digital dental models can be transformed into data formats suitable for machine learning, enabling automated analysis of complex features. Methods for cleaning and preprocessing digital scans are also improving, making the data more consistent and ready for large scale research.[7] Combining intraoral scanners with artificial intelligence is a natural progression in forensic dentistry. Three dimensional scans offer detailed representations of tooth shape, occlusal patterns, and the overall form of the dental arch, all of which may supply additional indicators for estimating age and sex. New computational methods show that digital dental models can be converted into formats that work well with machine learning, allowing complex features to be analyzed automatically. Techniques for refining and standardizing scan data are also advancing, making these digital records more uniform and better suited for large scale forensic studies. [8]

Artificial intelligence also raises both opportunities and challenges. While machine learning can uncover subtle patterns linked to age and sex, it

requires large and diverse datasets to avoid bias. If datasets are small or population specific, the resulting models may not generalize well to broader groups. Studies using panoramic radiographs in different populations have emphasized the importance of including a wide range of age groups and sexes to improve model robustness.[9] Extending these lessons to intraoral scans is essential for building reliable predictive systems. Standardized validation frameworks will be needed to ensure that these models meet forensic requirements for transparency and reproducibility.[10,11] This systematic review is therefore motivated by both scientific curiosity and practical necessity. By gathering and evaluating studies that investigate the role of intraoral scanners in forensic odontology, particularly for age and sex estimation, the review seeks to provide a clearer understanding of current evidence. It aims to identify the benefits, limitations, and methodological gaps, while offering directions for future research. In doing so, the review hopes to bridge clinical innovation with forensic application, supporting the development of tools that are accurate, reproducible, and fit for the operational demands of forensic science

METHODS

This narrative review was based on a targeted search of peer-reviewed literature published between 2016 and 2024. Sources were identified using PubMed, Scopus, and ScienceDirect with keywords such as “Intraoral Scanner,” “Digital Impression,” “Forensic Odontology,” “Age Estimation,” and “Sex Determination.” Additional references were drawn from relevant open-access journals in dentistry and forensic sciences to capture the breadth of current applications of intraoral scanners. Relevant articles were selected based on their applicability to forensic odontology, particularly studies that investigated the use of intraoral scanners for human identification, age estimation, or sex determination. Expert input from forensic odontologists and dental specialists was also considered to guide topic selection and ensure clinical and forensic relevance.

Applications of intraoral scanners in forensic odontology

Age estimation

Estimating age is one of the most important responsibilities in forensic odontology, especially in legal situations that involve children and in efforts to identify victims of disasters.[12] Intraoral scanners (IOS) provide accurate three-dimensional images of the dentition, allowing investigators to examine several age-related features. The introduction of intraoral scanner (IOS) has provided new opportunities by producing detailed three-dimensional digital images of the dentition. Unlike conventional impressions or radiographs, Intraoral scanner captures the surface morphology of teeth and surrounding oral structures with high accuracy and without exposure to radiation. Recent investigations have shown that intraoral scanners can be applied to measure tooth wear and eruption patterns with remarkable precision, making it a valuable alternative in age assessment procedures. [13] Intraoral scanners have been shown to produce accurate and consistent representations of dental anatomy. Their precision supports not only everyday clinical work but also forensic applications that require measurements to be objective and repeatable. This level of accuracy becomes particularly valuable when assessing small age-related changes in the teeth, such as cusp wear, variations in crown size, and alterations on the occlusal surface.[14]

Studies outside clinical dentistry have also emphasized the value of intraoral scanners for estimating age in forensic settings. Research in forensic science shows that three dimensional intraoral imaging can document age-related dental features with good reliability, providing an option that differs from conventional radiographic techniques. This is especially important in legal cases where reducing radiation exposure is required, and in mass disaster situations where quick and non-invasive data collection is urgently needed.[3] Intraoral scanners have been shown to capture dental morphology with a high degree of accuracy and consistency. This reliability makes them valuable not only in clinical practice but also in forensic work, where measurements must be objective and repeatable. Their precision is particularly beneficial when examining subtle age-related features such as cusp wear, changes in crown size, and modifications on the occlusal surface. Research in forensic science further supports their usefulness, revealing that three dimensional intraoral imaging can record age-related dental characteristics with dependable results, offering an alternative to conventional radiographic techniques. This is especially important in legal cases that limit radiation exposure and in mass disaster settings where fast and non-invasive data collection is crucial.[11]

Intraoral scanners offer precise and consistent digital records that can assist with age estimation in forensic odontology. Their accuracy, ease of use, and ability to store data digitally make them a strong addition to existing techniques. Even so, broader research involving varied populations and unified forensic guidelines is needed to fully validate their reliability and to support their adoption as a routine tool in forensic investigations

Sex determination

“Sex determination is a fundamental element of forensic odontology, serving as one of the key identifiers when constructing a biological profile for

an unknown person. With the use of intraoral scanners, palatal rugae and dental arch forms can now be captured in detailed three dimensional images. These anatomical features exhibit subtle differences between males and females, and digital recording enables examiners to assess them with improved consistency. Research on palatal rugae patterns has shown that, when analyzed with multivariate approaches such as logistic regression, data from intraoral scanners can produce moderate accuracy in estimating sex. These findings further highlight the potential value of intraoral scanners in forensic applications.[15] The reliability of intraoral scanners in documenting palatal vault geometry has also been investigated. Measurements such as palatal height, arch width, and curvature, when acquired digitally, have been shown to vary between males and females in ways that can support forensic distinction. Research indicates that even across populations with diverse craniofacial characteristics, digitized palatal features retain discriminative value, although overall accuracy remains moderate and further standardization is needed.[16]

Comparisons between traditional plaster models and digital impressions reveal another strength of intraoral scanners. Although both methods can reliably reproduce palatal rugae, digital scanning provides clear advantages in terms of speed, portability, and the ability to share data easily. These benefits are especially valuable in forensic work, where efficiency and secure long-term storage are essential. Recent studies have shown that digital palatal records are not only as dependable as plaster casts but also far more practical for use in larger or multi-institutional investigations. This suggests that intraoral scanners can support sex estimation by offering accurate, consistent, and easily archived digital representations of palatal and dental structures. While current predictive accuracy varies from moderate to relatively high depending on the analytical method used, advancements in statistical modeling and artificial intelligence are likely to enhance these outcomes. Ongoing research that includes larger and more diverse populations will be vital for strengthening the method's forensic validity and ensuring that digital records are accepted within medicolegal settings.[17]

Human Identification

Human identification remains a core task in forensic odontology, particularly when dealing with mass disasters, advanced decomposition, or fragmented remains. In these circumstances, traditional approaches such as fingerprint analysis or DNA profiling may not be feasible, creating a need for alternative methods. Intraoral scanners present a promising solution by generating detailed three dimensional images of the palate and dental arches, anatomical structures that are stable and distinctive to each individual. Research has shown that palatal vault measurements captured with these scanners can identify individuals with sensitivity exceeding ninety percent and specificity close to ninety eight percent, highlighting their potential as reliable biometric markers in forensic investigations. The consistency of palatal rugae recorded through intraoral scanning has also been evaluated, and unlike conventional plaster casts, digital impressions do not degrade over time and can be stored indefinitely. Digital records further offer advantages in speed, portability, and ease of sharing between institutions, making them well suited to modern forensic workflows.[17] Further support comes from research focusing on the reliability of repeated digital scans. Intraoral scanner records of palatal morphology were consistent and stable even when multiple scans were taken under different conditions. This consistency highlights their suitability for forensic identification, where even minor errors in measurement could affect the credibility of evidence presented in court.[16] Taken together, these studies present a compelling case for intraoral scanners as a modern tool in human identification. The ability to produce unique, reproducible, and easily stored digital dental records offers an advantage that goes beyond traditional impressions. While more research is still needed to validate their application across larger and more diverse populations, the current evidence suggests that intraoral scanners can play a transformative role in forensic identification, helping to bridge gaps when conventional techniques are limited or unavailable.

Advantages of intraoral scanners over conventional methods

The introduction of intraoral scanners has transformed the way forensic odontology can be practiced, offering advantages that go far beyond those of conventional approaches. One of the most significant benefits is the superior accuracy and reproducibility of digital scans. High-resolution three-dimensional records allow for precise measurement of dental and palatal morphology while minimizing the risk of subjective errors that often accompany plaster models. Recent research has shown that intraoral scanner data are more consistent and reliable than physical casts, making them more suitable for detailed forensic analysis. [16] Another important advantage is the comfort and non-invasive nature of digital scanning. Traditional impressions are often uncomfortable and can be technically challenging, especially in delicate post-mortem conditions. In contrast, intraoral scanners capture the necessary information quickly and with minimal disturbance to oral structures. Studies comparing plaster models and

digital scans have confirmed that both methods reproduce palatal rugae accurately, yet the digital approach is safer, faster, and more efficient in forensic settings. [17]

Digital records also offer unparalleled advantages in terms of storage and accessibility. Unlike plaster casts, which may fracture or degrade over time, electronic files remain intact and can be archived indefinitely. The ability to share these records instantly across institutions, whether locally or internationally, greatly accelerates collaboration in forensic investigations. Furthermore, repeated scans have demonstrated stable results under different conditions, reinforcing the reliability of intraoral scanners for long-term forensic use.[16] The integration of artificial intelligence adds another dimension to their value. Digital datasets generated by intraoral scanners can be processed using machine learning algorithms to detect subtle patterns that may be difficult for the human eye to recognize. This development not only improves accuracy in estimating age and sex but also opens the possibility of automated identification systems that are both rapid and efficient.[19]

Limitation and Challenges

While intraoral scanners hold significant promise for forensic odontology, several limitations still stand in the way of their full integration into forensic work. Recognizing these challenges is essential before the technology can be applied routinely. The main concerns involve technical performance, limited study populations, operator-related variation, differences among scanner models, and questions about legal acceptance and ethical use. One major issue is the inconsistency in accuracy between different scanner systems. Another challenge arises from the small and often homogenous samples used in existing studies. Much of the current research includes fewer than one hundred participants and typically focuses on a single ethnic group. This narrow scope makes it difficult to apply the findings broadly, since features such as palatal rugae patterns and dental arch dimensions can differ across populations, and sexual dimorphism seen in one group may not appear in another. Until larger, multiethnic validation studies are conducted, the use of intraoral scanner data in forensic casework will remain limited.[13]

The absence of standardized forensic protocols represents another important challenge. At present, there is no universal guideline on how intraoral scanner data should be collected, stored, and analyzed for forensic purposes. This creates inconsistencies between studies and raises concerns regarding reproducibility. While some studies rely on manual morphometric analysis, others employ advanced statistical methods or machine learning algorithms, leading to considerable heterogeneity in outcomes. The lack of standardization makes it difficult to compare findings across investigations and slows the establishment of normative databases that would be necessary for practical forensic application [18] The skill and training of the operator also influence how reliable intraoral scanner data can be. Even though these devices are designed to be easy to use, obtaining accurate and complete digital impressions still requires proper technique and experience. Missing areas or acquisition errors can reduce the quality of the digital record. The challenge becomes greater in postmortem situations, where conditions such as rigor mortis, fragile tissues, or traumatic injuries can make scanning more difficult. Studies involving postmortem intraoral imaging have shown that while scanning is possible, it demands technical adjustments and specialized training. These findings suggest that intraoral scanners cannot be fully relied upon in forensic mortuaries until these practical challenges are addressed.[20,21]

Cost and accessibility also limit the wider use of intraoral scanners. These devices are still relatively expensive to purchase and maintain, which can be a significant hurdle for low- and middle-income countries where forensic resources are already limited. The challenge is intensified by the fact that the forensic use of intraoral scanners remains largely experimental, making institutions hesitant to invest in technology that has not yet been fully validated for courtroom purposes. In addition, storing large digital files requires secure servers and reliable backup systems, creating further financial demands. Legal and ethical issues add another layer of complexity. For digital records to be accepted in court, they must meet strict requirements for authenticity, reliability, and proper chain of custody. Because intraoral scanner data have not yet been widely examined in legal settings, their value as evidence remains uncertain. The collection and storage of biometric dental information also raise concerns regarding privacy and consent, particularly if such data are included in national or international forensic databases. There is also potential for misuse if these digital records are not properly regulated. Addressing these ethical and legal considerations will be essential before intraoral scanners can be fully integrated into routine forensic practice.[20]

Another limitation relates to technological dependency. The reliance on software for processing and analyzing intraoral scanner data introduces the risk of algorithmic errors or software incompatibilities. Files generated by one scanner may not be compatible with analysis software designed for another, creating obstacles in data sharing and interoperability. Moreover, if artificial intelligence is applied to analyze intraoral scanner data, transparency

and explainability of algorithms become critical. Courts may be hesitant to accept forensic conclusions based on "black-box" AI models that cannot be clearly explained. Establishing transparent and validated workflows will therefore be crucial for long-term adoption. Time efficiency, while often cited as an advantage, can also be a limitation in certain contexts. Scanning a full dental arch requires time, and the process may be further slowed in post-mortem cases due to anatomical challenges. While faster than conventional impressions in living subjects, intraoral scanning of deceased individuals may require special positioning, tissue preparation, or auxiliary equipment, which could limit its practicality in high-volume forensic scenarios.[22]

Conclusion

Intraoral scanners are emerging as a valuable innovation in forensic odontology because they can produce precise, long-lasting digital records that assist in age estimation, sex determination, and human identification. Their ability to capture three dimensional details of features such as palatal rugae, dental arch form, and age-related dental changes positions them as a strong alternative to traditional stone models and radiographic imaging. However, their wider adoption is still limited by variations between scanner systems, small and often population-specific study samples, the lack of unified forensic protocols, and questions about how digital evidence will be evaluated in legal settings. Future progress will rely on larger studies across diverse groups, clear standards for scanning and interpretation, and the integration of advanced computational methods. Pairing intraoral scanners with artificial intelligence may enhance the accuracy and efficiency of forensic assessments, while careful consideration of legal and ethical requirements will be essential to maintain credibility. With ongoing research and collaboration, intraoral scanners have the potential to become a regular part of forensic workflows and to strengthen the dependability of age and sex estimation moving forward.

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