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Revolutionizing Forensic Odontology with Artificial Intelligence: A Comprehensive Review

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Abstract
Artificial Intelligence (AI) has revolutionized several branches of forensic science, including forensic odontology, by introducing automation, objectivity, and enhanced diagnostic accuracy. In dental forensics, AI facilitates crucial tasks such as bite mark analysis, age estimation, and sex determination—areas traditionally influenced by human subjectivity. Modern computational tools like machine learning (ML), deep learning (DL), and convolutional neural networks (CNNs) enable rapid processing and analysis of complex dental and skeletal datasets. This review explores the progressive integration of AI into forensic odontology, emphasizing its practical applications, advantages, limitations, and ethical considerations. The study also discusses future perspectives, highlighting the growing role of AI in supporting medico-legal investigations and disaster victim identification. Literature for this review was obtained from databases including PubMed, Medline, IEEE Xplore, and Google Scholar up to December 2023.

Keywords: Artificial Intelligence, Forensic Odontology, Machine Learning, Deep Learning, Bite Mark Analysis, Age Estimation, Sex Determination, Dental Identification, Convolutional Neural Networks, Ethics in AI

1. INTRODUCTION

Forensic odontology is a vital subdiscipline of forensic science that applies dental knowledge to legal investigations. It aids in human identification, sex determination, age estimation, and assessment of abuse or trauma-related cases[1]. Teeth and associated maxillofacial structures are among the most resilient components of the human body, capable of resisting decomposition, high temperatures, and physical damage. Hence, dental evidence often provides the only reliable clue in complex cases of mass disasters, fire accidents, or decomposed remains[2,3]. Even partial dentition, restorations, or unique dental morphology can significantly assist in personal identification during medico-legal examinations[4].

Historically, forensic odontology has depended on manual methods, including visual comparison of dental

records, bite mark overlays, and cephalometric analyses. Although effective, these methods are often time-consuming, operator-dependent, and subject to inter-examiner variability[5,6]. In contemporary forensic practice, where accuracy and speed are critical, such limitations have prompted the adoption of digital and computational technologies[7].

Artificial intelligence, defined as the simulation of human cognitive processes by machines, has emerged as a transformative tool in healthcare and forensic applications[8]. Within odontology, AI-based systems—especially those utilizing ML, DL, and CNN algorithms—have demonstrated significant promise in identifying patterns, analyzing radiographs, and minimizing examiner bias[9,10]. For instance, AI models trained on orthopantomographs (OPGs), dental impressions, and morphometric data can outperform traditional statistical approaches in tasks such as sex determination and dental age estimation[11,12].

Additionally, the increasing use of digital dental records and cloud-based forensic databases allows AI systems to perform rapid cross-matching for victim identification across large populations[13,14]. Consequently, the field of forensic odontology is transitioning from manual, experience-based methodologies to data-driven, automated systems enhanced by computational intelligence.

This review discusses major applications of AI in forensic odontology—including bite mark analysis, age estimation, and gender determination—while addressing the technology's limitations, ethical implications, and future potential.

2. Applications of AI in Forensic Odontology

2.1 Bite Mark Identification

Bite marks are significant forensic indicators in criminal cases involving assault, homicide, or child abuse[6]. Traditional analysis, which relies on visual overlays and manual comparison, has faced criticism due to its subjectivity and limited reproducibility[5,6]. AI introduces an objective framework for analyzing bite patterns, reducing human bias. Mahasantipiya et al.[7] developed an artificial neural network (ANN) model that utilized parameters such as inter-canine distance, incisor angulation, and curvature patterns. The model demonstrated superior accuracy and reduced inter-examiner variation compared to traditional methods. AI-based image analysis can quantify shape descriptors and pattern features more consistently than visual inspection, enhancing evidentiary reliability. Nevertheless, AI should complement, not replace, expert interpretation to maintain the integrity of forensic conclusions[13,15].

2.2 Gender Determination

Sex estimation forms a cornerstone of forensic profiling, particularly in cases where only partial or skeletal remains are available. Due to pronounced sexual dimorphism, teeth—especially canines—serve as robust indicators for gender differentiation[8]. Conventional morphometric and statistical analyses often yield population-specific results with varying reliability. AI-based methods overcome such limitations by recognizing subtle, non-linear features in dental images. Patil et al.[9] applied ANN models to panoramic radiographs of over 500 individuals, achieving higher accuracy than traditional discriminant analysis. CNN architectures have further refined this process by automatically learning spatial hierarchies in image data, achieving high sensitivity and specificity in identifying sex[14]. These methods offer rapid and standardized results, minimizing examiner dependency while improving accuracy across populations.

2.3 Age Estimation

Estimating chronological age plays a crucial role in civil and criminal investigations, immigration cases, and victim identification. Conventional approaches—such as Demirjian's method or hand–wrist radiographs—are prone to observer variation and population bias[2,4]. AI techniques, particularly CNN-

based frameworks like DANet and DASNet, have revolutionized this field. Blanco et al.[10] reported that DASNet achieved a correlation coefficient of 0.90 with a mean prediction error of less than one year in individuals below 15 years. Similarly, automated age estimation systems employing OPG datasets have demonstrated consistency across diverse ethnic groups[11,12]. The integration of AI significantly reduces processing time and enhances precision, making it invaluable for large-scale forensic and disaster victim investigations.

2.4 Additional Forensic Applications

Beyond its primary roles in bite mark, age, and sex assessment, AI has expanded its relevance to several other domains of forensic odontology. Automated dental record comparison, particularly in disaster victim identification (DVI), has drastically improved operational efficiency. During events such as the 2004 Indian Ocean tsunami, the implementation of digital dental databases enabled quicker cross-referencing of dental records with victims' data[3]. Moreover, AI algorithms have been utilized to analyze palatal rugae and lip prints—unique biometric features that can assist in personal identification[13]. Recent studies also highlight AI's utility in detecting dental anomalies and pathologies, providing auxiliary information for both forensic and clinical contexts[14]. Collectively, these developments illustrate AI's expanding role in enhancing accuracy, objectivity, and scalability in forensic investigations.

3. Limitations

Despite remarkable advancements, AI in forensic odontology faces significant obstacles that hinder widespread implementation:

1. **Data scarcity and variability:**
   Most AI models rely on limited, region-specific datasets. The lack of standardized, population-representative samples reduces the generalizability of outcomes[16].
2. **Continuous technological evolution:**
   AI algorithms evolve rapidly, often rendering older models obsolete. Forensic applications therefore require continuous validation and adaptation to maintain reliability.
3. **Validation and reproducibility:**
   A majority of studies are pilot-based or conducted under controlled conditions, lacking large-scale validation in real forensic casework[5,15].
4. **Ethical and legal concerns:**
   The use of dental and facial data raises critical issues regarding privacy, informed consent, and potential misuse of biometric information[17]. Establishing ethical standards and legal oversight is crucial for responsible AI integration.

Overcoming these barriers requires interdisciplinary collaboration among forensic experts, data scientists, and policymakers to ensure ethical, transparent, and scientifically validated AI deployment.

4. Future Scope and Ethical Considerations

The future of AI in forensic odontology is exceptionally promising. Proposed advancements include centralized databases for dental and bite mark biometrics of populations such as airline passengers, military personnel, and high-risk occupational groups[15]. Such repositories could expedite identification in mass disasters or combat zones. However, they raise significant ethical issues related to data ownership, informed consent, and the potential misuse of personal information.

Developing globally standardized and ethically governed AI systems is paramount. International

collaboration can help establish diverse datasets that enhance model accuracy and reduce population bias[16]. Furthermore, integrating AI into routine forensic workflows demands robust data encryption, algorithmic transparency, and clear accountability frameworks[17]. Training forensic practitioners to interpret AI-generated outputs responsibly will ensure that human judgment remains central to medico-legal decision-making.

5. Conclusion

Artificial intelligence has significantly transformed the landscape of forensic odontology, enabling faster, more precise, and objective evaluations in areas such as bite mark identification, age estimation, and sex determination. Compared to traditional manual approaches, AI-driven methods demonstrate superior consistency and efficiency. However, the successful adoption of AI in forensic practice depends on the establishment of standardized datasets, large-scale clinical validation, and adherence to ethical and legal principles. As digital transformation accelerates across forensic sciences, AI is poised to become an indispensable tool, reinforcing the accuracy, credibility, and scope of forensic odontology in the pursuit of justice.

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