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Advances in forensic dentistry: the role of technology in human identification

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Abstract

Forensic dentistry is essential in human identification, especially in mass disasters, criminal investigations, and unidentified remains. This qualitative and descriptive literature review examines advancements in forensic dentistry from 2010 to 2025, focusing on emerging technology like artificial intelligence (AI) and digital methods, including virtual autopsy (virtopsy). Key innovations discussed are digital radiography, cone-beam computed tomography, AI-driven image analysis for dental record matching, and non-invasive virtopsy for postmortem examination. These tools enhance precision, efficiency, and automation in identifying human remains. Artificial intelligence contributes significantly by improving pattern recognition and predictive modeling, though challenges persist, including ethical concerns, data privacy, algorithmic bias, and legal integration. The study underscores that, while these technologies elevate forensic practices, their success depends on interdisciplinary collaboration and standardized protocols. Combining innovation with traditional methods ensures reliability and offers a transformative future for forensic dentistry.

Keywords: forensic dentistry, human identification, artificial intelligence, digital methods, virtopsy, technological advancements

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Достижения в судебной стоматологии: роль технологий в идентификации личности

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Резюме

Судебная стоматология играет ключевую роль в идентификации личности, особенно в условиях массовых катастроф, уголовных расследований и при работе с неопознанными останками. Настоящий качественный описательный обзор литературы охватывает достижения в области судебной стоматологии за период с 2010 по 2025 г., с акцентом на внедрение новых технологий, включая искусственный интеллект и цифровые методы, такие как виртуальная аутопсия (virtopsy). К числу ключевых инноваций относятся цифровая радиография, конусно-лучевая компьютерная томография, анализ изображений на основе искусственного интеллекта для сопоставления стоматологических данных, а также

неинвазивная виртуальная аутопсия для посмертного исследования. Применение данных технологий способствует повышению точности, эффективности и автоматизации процессов идентификации человеческих останков. Искусственный интеллект вносит значительный вклад за счет совершенствования распознавания паттернов и предиктивного моделирования, однако его использование сопровождается рядом ограничений, включая этические аспекты, вопросы конфиденциальности данных, алгоритмическую предвзятость и сложности правовой интеграции. В работе подчеркивается, что, несмотря на значительное расширение возможностей судебной практики, эффективность данных технологий во многом зависит от междисциплинарного взаимодействия и стандартизации протоколов. Интеграция инновационных решений с традиционными методами обеспечивает надежность результатов и формирует основу для трансформационного развития судебной стоматологии.

Ключевые слова: судебная стоматология, идентификация личности, искусственный интеллект, цифровые методы, виртуальная аутопсия, технологические инновации

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INTRODUCTION

Forensic dentistry, a specialized branch of dentistry, intersects legal medicine and dental science to aid in the identification of individuals through analysis of oral structures, particularly in cases of decomposed, mutilated, or skeletonized remains [1]. Human identification is a cornerstone of forensic investigations, encompassing antemortem (pre-death) and postmortem (after death) comparisons of dental records, bite marks, and craniofacial features.

The reliability of dental evidence stems from its resistance to postmortem changes – teeth endure extreme temperatures, chemicals, and trauma better than soft tissues – making the Dentistry methods indispensable in scenarios like mass fatalities from natural disasters, aviation accidents, or terrorist attacks [2]. Historically, forensic dentistry relied on manual comparisons of radiographs, casts, and charts, a process prone to subjectivity and time constraints.

The advent of digital technology and artificial intelligence (AI) has transformed this field, introducing precision, speed, and objectivity. Digital tools such as cone-beam computed tomography (CBCT) enable three-dimensional (3D) reconstructions of dental arches, while AI algorithms automate matching processes, reducing human error [3]. Virtopsy, a non-invasive postmortem imaging technique using CT and MRI, further minimizes the need for traditional autopsies, preserving evidence of integrity and respecting cultural sensitivities [4].

The integration of AI in forensic dentistry addresses escalating demands in global forensics. For instance, during the Malaysia Airlines Flight 17 air crash, dental records facilitated identification of several victims, but delays highlighted the need for automated systems [5]. AI, leveraging machine learning (ML) and deep learning (DL), excels in pattern recognition – analyzing occlusal surfaces, restorations, and pathologies with accuracies exceeding 90% in controlled studies [6]. Yet, these advancements raise ethical dilemmas: data security, bias in training datasets (often skewed toward

certain demographics), and the admissibility of AI-generated evidence in courts [7].

This narrative review aims to analyze technological advances in human identification within forensic dentistry, focusing on digital methods and AI's impact. Specific objectives include: (1) describing principal technology used; (2) evaluating AI's contributions to the Dentistry record analysis and identification automation; and (3) discussing limitations, challenges, and future perspectives. By synthesizing literature from 2010 to 2025, this work provides a comprehensive overview, informing practitioners, researchers, and policymakers on optimizing these tools for ethical, efficient forensic practice.

The rationale for this review lies in the rapid evolution of technology amid rising forensic caseloads. The COVID-19 pandemic, for example, accelerated virtopsy adoption to reduce biohazard risks, while Interpol's disaster victim identification (DVI) protocols promise scalability [8; 9]. However, disparities in access, particularly in low-resource settings, underscore the need for equitable implementation. This article posits that while technology enhance identification efficacy, their success hinges on robust validation, training, and interdisciplinary integration.

MATERIALS AND METHODS

This study constitutes a narrative literature review of qualitative, exploratory, and descriptive nature, aimed at analyzing and discussing scientific outputs on human identification via forensic dentistry, with emphasis on technological advancements from AI incorporation and digital methods like virtopsy. Narrative reviews, unlike systematic ones, do not mandate exhaustive searches or quantitative meta-analyses; instead, they synthesize existing knowledge to offer a holistic understanding of conceptual and technical shifts in contemporary forensic dentistry [9]. This approach facilitates the integration of diverse perspectives – theoretical frameworks, empirical case studies, and technological applications – providing insights into evolving practices without rigid statistical constraints.

The methodological procedures encompassed a comprehensive bibliographic search and material selection. Sources were drawn from reputable databases, including PubMed, Scopus, Web of Science, SciELO, and Google Scholar, ensuring a broad representation of peer-reviewed literature. Search terms combined Boolean operators: (“forensic dentistry” OR “forensic dentistry”) AND (“human identification” OR “dental identification”) AND (“artificial intelligence” OR “AI” OR “machine learning” OR “digital methods” OR “virtopsy” OR “CBCT” OR “3D imaging”). Filters applied included publication dates from 2010 to 2025 (capturing post-digital revolution developments), full-text availability, and languages: Portuguese, English, or Spanish, reflecting the multilingual forensic research landscape in Latin America and globally.

Inclusion criteria prioritized articles directly or indirectly addressing forensic dentistry’s application in human identification, AI usage, virtopsy, or related ethical/technical aspects. Eligible works included original research, reviews, case reports, and technical notes from journals in dentistry, forensic sciences, and biomedical engineering. Exclusion criteria eliminated non-peer-reviewed materials (e.g., editorials, abstracts), studies predating 2010, or those unrelated to Dentistry identification (e.g., pure AI applications in general medicine). Duplicates were removed using reference management software (EndNote X9), and relevance was assessed via title/abstract screening, followed by full-text review.

The search yielded 1,247 initial results; after deduplication and screening, 156 articles were selected for in-depth analysis. Data extraction focused on key themes: technology descriptions, AI contributions (e.g., accuracy metrics, automation workflows), limitations (e.g., validation gaps), and prospects (e.g., regulatory

needs). Synthesis was thematic, grouping findings into technology overviews, AI evaluations, and challenge discussions. No formal quality appraisal was conducted, per narrative review conventions, but seminal works were prioritized for their citation impact and methodological rigor (e.g., studies with >100 citations).

Ethical considerations aligned with narrative review standards; no human subjects were involved, obviating institutional review board approval. Limitations include potential publication bias toward positive outcomes and the exclusion of gray literature, which may overlook emerging, unpublished innovations. Nonetheless, this methodology ensures a balanced, interpretive synthesis, illuminating forensic dentistry’s technological trajectory.

RESULTS

Technological advancements in human identification

Human identification in forensic dentistry traditionally hinges on comparative analysis of antemortem dental records – radiographs, charts, and photographs – with postmortem findings. Technological strides have digitized and automated this process, enhancing precision amid complex cases. This section delineates main identification methods, from imaging modalities to AI integrations, underscoring their transformative impact. Digital radiography and intraoral scanners represent foundational advances. Conventional film-based X-rays have largely yielded to charge-coupled device (CCD) sensors and photostimulable phosphor plates, offering instantaneous images with reduced radiation (up to 80% lower) and superior resolution [10]. In Table 1, a compilation of the human identification in forensic dentistry could be found, with their advantages and limitations.

Table 1. Main methods of human identification in forensic dentistry, with their advantages and limitations

Таблица 1. Основные методы идентификации человека в судебной стоматологии с их преимуществами и ограничениями

Method	Advantages	Limitations
Traditional Forensic Dentistry	Dental evidence resists extreme conditions; crucial in mass fatalities	Manual, subjective, and time-consuming comparisons
Digital Radiography	Instant, high-resolution images with reduced radiation	Foundational, but less detailed than 3D imaging for complex cases
Cone-Beam Computed Tomography (CBCT)	Provides 3D volumetric data, highly accurate for dental anomalies, expedites identification	High cost, requires expertise, susceptible to degraded remains, lacks protocol standardization
Surface Scanning	Generates precise 3D models of dental structures; aids bite mark analysis	Bite mark analysis remains a contentious technique
Virtopsy (CT/MRI)	Non-invasive, preserves remains, high concordance with traditional methods, safer for infectious cases	High cost, requires specialized expertise, accessibility barriers
Artificial Intelligence (AI) for Dental Analysis	Automates matching, high accuracy in pattern recognition, reduces errors and processing time, aids predictive analytics	Ethical concerns (bias, privacy), “black box” nature, high cost, training needs, lack of regulatory guidelines, accuracy drops with degraded data
AI in Bite Mark Analysis	Mitigates subjectivity, detects specific characteristics, higher intra-observer agreement than humans	Bite mark analysis remains historically controversial
Pulp DNA Analysis	Reliable genetic material from dental pulp, even in extreme conditions; high precision and resilience	Degradation, contamination, and high costs in slow processes

These enable detailed visualization of restorations, endodontics, and periodontal status, critical for matching. CBCT, introduced in the early 2000s, provides volumetric data for 3D reconstructions of maxillofacial structures, invaluable in fragmented remains [12]. CBCT's isotropic voxels (0.075–0.4 mm) facilitate multiplanar views, quantifying dental anomalies like taurodontism or supernumerary teeth with 95–98% accuracy [13]. In DVI operations, post-mortem CBCT serves as an alternative or supplement to conventional autopsy in mass disasters; however, to ensure accurate diagnoses and avoid erroneous conclusions, specialized technical training is required [12; 14].

Surface scanning methods, including laser and structured light scanners, generate 3D models of dental casts or impressions. Devices like the iTero Element scanner achieve sub-millimeter precision, enabling virtual superimposition for bite mark analysis – a contentious but evolving technique [15]. Integration with CAD/CAM software allows simulation of antemortem alignments, reducing subjectivity in court-admissible evidence. Virtopsy emerges as a paradigm shift in post-mortem examination. Coined by Buck et al. [15], it employs multislice CT (MSCT) and magnetic resonance imaging (MRI) for non-invasive autopsies, minimizing tissue disruption [16].

In the Dentistry contexts, virtopsy visualizes dental structures without scalpel incision, detecting foreign bodies (e.g., fillings) or fractures obscured by trauma. A study of 50 virtopsies reported 92% concordance with traditional methods for dental identification, with added benefits in radiation-safe imaging of pediatric or infectious cases [16–18]. Limitations include cost (CT scanners ~\$1–2 million) and expertise requirements, yet portable units are mitigating accessibility barriers. These digital tools form the substrate for AI augmentation. AI, encompassing ML subsets like convolutional neural networks (CNNs), processes vast datasets to automate identifications. For instance, AI algorithms trained on dental panoramic radiographs (OPGs) classify restorations (amalgam vs. composite) with 89% sensitivity [19].

In human identification, AI excels at landmark detection – identifying cusps, fissures, and root morphologies – for automated matching. A pilot using DL on 1,000 CBCT scans achieved 96.7% accuracy in dental arch superimposition, outperforming manual methods by 25% in time efficiency [20]. AI's forensic applications extend to predictive analytics. Generative adversarial networks (GANs) reconstruct missing antemortem data from partial postmortem scans, useful in burned remains [21]. Ethical AI frameworks, such as those from the American Board of Forensic Dentistry (ABFO), emphasize transparency to counter “black box” critiques, ensuring explainable outputs for judicial scrutiny [21].

To the transition of forensic dentistry from artisanal practices to data-driven science it is necessary to have a robust infrastructure, a multidisciplinary integration, as well as specialized technical expertise and ethical frameworks, ensuring standardized protocols that elevate the objective accuracy and evidentiary strength of dental records [22].

Contributions of artificial intelligence to forensic analysis

Artificial intelligence has revolutionized forensic dentistry by automating labor-intensive tasks, enhancing diagnostic accuracy, and enabling scalable identifications [3]. This section evaluates AI's specific contributions to dental record analysis and process automation, drawing on empirical evidence. In record analysis, AI streamlines antemortem-postmortem comparisons [6]. Traditional methods involve visual inspection of charts for caries, prosthetics, or orthodontics – error-prone under fatigue or volume. ML models, trained on annotated datasets (e.g., 10,000+ radiographs), employ feature extraction to quantify attributes: tooth number (FDI system), morphology, and pathology [19].

A CNN-based system developed by Japan's National Research Institute achieved 94.2% precision in matching OPGs, using Euclidean distance metrics for spatial alignment [23]. Similarly, in Brazil's forensic institutes, AI pilots reduced matching time from hours to minutes, vital for mass disasters [24]. Automation extends to bite mark analysis, historically controversial due to variability [25]. AI mitigates subjectivity via 3D scanning and neural networks that detect class (general) and individual (unique) characteristics, such as arch width or cusp patterns. A study using support vector machines (SVM) on 200 bite marks reported 85% intra-observer agreement, surpassing human experts (69%) [26].

Deep learning variants, like recurrent neural networks (RNNs), incorporate temporal data from video bites, enhancing admissibility in sexual assault cases. AI's predictive capabilities further identification. Anomaly detection algorithms flag inconsistencies (e.g., mismatched restorations), while natural language processing (NLP) parses textual records for keywords like “crown” or “extraction”. In virtopsy integration, AI segments dental volumes from CT data, automating segmentation with U-Net architectures – achieving Dice coefficients >0.90 for tooth isolation [27; 28].

A European consortium's AI-virtopsy tool identified 98% of victims in simulated scenarios, outperforming radiologists [29]. Quantitative impacts are profound: AI reduces false positives by 40% in diverse populations, addressing bias through augmented datasets (e.g., including underrepresented ethnicities) [30]. By preserving the body's integrity, AI-virtopsy is essential in complex forensics, cases involving charred remains, or when there are religious restrictions regarding conventional autopsy [31–33]. Artificial intelligence algorithms have proven to significantly accelerate the identification process, particularly through deep learning applied to panoramic radiographs, achieving high accuracy rates and automating labor-intensive matches [34].

AI also fosters education and simulation. Virtual reality (VR) platforms with AI simulate forensic scenarios, training odontologists in identification protocols [34]. These contributions democratize expertise, particularly in resource-limited regions.

DISCUSSION

The synthesis of this review illuminates a dynamic evolution in forensic dentistry, where digital and AI transcend traditional boundaries, fostering unprecedented efficiency in human identification. From CBCT's volumetric insights to AI's predictive prowess, these innovations address forensic imperatives: rapidity, accuracy, and reliability [3;12; 35]. Empirical evidence underscores their efficacy; for instance, The integration of advanced imaging methods, such as Computed Tomography (CT), has fundamentally transformed Disaster Victim Identification (DVI) workflows, allowing for rapid triage [35; 36]. Theoretically, these advancements align with forensic science's shift toward evidence-based paradigms, echoing the National Academy of Sciences' call for quantifiable methods [37]. AI's automation mitigates cognitive biases inherent in manual comparisons, aligning with psychological research on observer variability [38].

In *virtopsy*, non-invasiveness respects deontological principles, particularly in multicultural contexts where autopsies evoke taboos [8; 16; 17]. However, the discussion must confront disparities. While high-income nations leverage AI, developing regions rely on antiquated charts, perpetuating "forensic apartheid" [39]. Case studies from Latin America highlight this: operations following Brazil's 2019 Brumadinho dam disaster relied heavily on dental records and emerging digital tools for the complex identification of victims in challenging conditions [24]. Global initiatives, like INTERPOL's DVI, aim to bridge gaps through open-source platforms [9].

The integration of advanced imaging methods, such as Computed Tomography (CT), has fundamentally transformed Disaster Victim Identification (DVI) workflows, allowing for rapid and non-destructive triage [35].

Ethical discourse is paramount. AI's dual-use potential – beneficial in forensics, risky in surveillance – demands safeguards. The Asilomar AI Principles advocate human oversight, ensuring the Dentistry AI augments rather than supplants judgment [36]. Bias mitigation via inclusive datasets is crucial; recent audits reveal 15–20% error hikes for non-Western populations, necessitating decolonized data strategies [30]. Prospectively, convergence with biotechnology – AI-analyzed dental microbiomes or epigenetics – could enable "soft" identifications from minimal samples [36]. Regulatory evolution, including ISO standards for forensic AI, will enhance credibility [40; 41]. Educational reforms must embed tech literacy in curricula, as evidenced by successful VR simulations, boosting proficiency by 35% [34].

In sum, this review concluded that new methods have important pivotal role yet emphasizes holistic adoption: technical prowess must harmonize with equity, ethics, and evidence. Forensic dentistry stands at an inflection point, poised to safeguard identities in an increasingly complex world.

Despite advancements, forensic dentistry's technological integration faces multifaceted limitations and challenges, necessitating critical discourse. Technical limitations include data quality and interoperability. Postmortem alterations, such as: carbonization, frag-

mentation – degrade imaging, with AI accuracies dropping to 70% in compromised samples [42].

Although the dental pulp provides viable genetic material even when teeth are subjected to extreme temperature conditions and trauma [2], Pulp DNA Analysis faces practical obstacles in forensic dentistry. Its main limitations involve the complexity of the extraction process, which makes it susceptible to contamination and severe degradation in excessively fragmented or charred remains [42]. Furthermore, the high costs and slow laboratory processing time delay its swift application in mass disaster scenarios.

Training datasets often lack diversity, perpetuating biases: models trained on Caucasian dentition underperform on Asian or African morphologies, yielding equity gaps [43]. Standardization eludes varying imaging protocols (e.g., voxel sizes in CBCT) impede cross-jurisdictional comparisons, as seen in international DVI efforts [44]. Ethical and legal challenges loom large. AI's opacity raises admissibility concerns under Daubert standards – courts demand explainability, yet DL "black boxes" obscure decision rationales [45]. Privacy risks escalate with biometric data: GDPR and HIPAA compliance is mandatory, but breaches in cloud-based AI systems could expose sensitive records [7]. Forensic equity is another hurdle; low-income countries lag in adoption, exacerbating global disparities – only 20% of African nations employ digital dentistry routinely [46].

Implementation barriers involve cost and training. High-end CBCT/*virtopsy* setups (~\$500,000) and AI software licenses strain budgets, while odontologists require upskilling – surveys show 60% feel underprepared for AI (American Dental Association, 2023). Regulatory voids persist: no universal guidelines exist for AI validation in forensics, unlike FDA approvals for medical AI. Future perspectives are optimistic. Hybrid AI-human workflows could hybridize strengths, with federated learning enabling privacy-preserving model training across institutions [16; 17; 47].

Advances in edge computing will facilitate on-site AI processing in disasters, while blockchain ensures tamper-proof records [9]. Ethical AI frameworks, like those proposed by the ABFO, advocate bias audits and diverse datasets [21]. However, it is important to emphasize that these tools reduce human error and accelerate the identification process in mass disasters by transforming dental patterns into precise biometric data. For full confidence and medico-legal validity, they must function as an ally to the professional rather than a replacement [48].

The necessity of interdisciplinary integration in human identification across borders and institutions is paramount to ensure forensic accuracy and global security. Robust international cooperation facilitates the standardization of protocols and the seamless exchange of genetic, dental, and osteological data essential for resolving complex transnational cases. This collaborative framework optimizes investigative outcomes by harmonizing multidisciplinary expertise and technological resources within a unified forensic network [9]. Addressing these challenges requires invest-

ment in validation studies, policy reforms, and education. By surmounting barriers, the new technological methods can fully realize their potential, fortifying forensic dentistry's role in law and humanitarian efforts.

CONCLUSION

Forensic dentistry has made significant strides in human identification, with the use of pulp DNA emerging as a landmark method. This literature review ex-

plores the challenges and advancements in this field, emphasizing the unique role of dental pulp as a reliable source of genetic material, even in scenarios involving extreme conditions like decomposition or incineration. By highlighting its precision and resilience compared to traditional methods, the study underscores the potential of pulp DNA in forensic investigations, setting a new standard in accuracy and reliability for human identification.

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All the authors made equal contributions to the manuscript preparation in terms of the idea and design of the article; data collection; critical revision of the article in terms of significant intellectual content and final approval of the version of the article for publication.

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