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REVIEW ARTICLE

From Pixels to Evidence: A Narrative Review of Digital Imaging Technologies in Forensic Odontology.

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Abstract

The integration of digital imaging in forensic odontology has greatly revolutionized the field in terms of accuracy, efficiency, and reproducibility of medicolegal investigations. Although conventional radiographic techniques still form the foundation, there is a growing trend toward complementing and replacing them with more advanced digital modalities that provide high-quality images, lower radiation doses and seamless data transmission.

This narrative review focuses on examining the range of digital technologies used in forensic dentistry, including digital radiography, cone beam computed tomography (CBCT), digital dental photography, three-dimensional scanning, photogrammetry, virtual autopsy and artificial intelligence–assisted analysis. A literature search was performed in PubMed, Scopus, and Google Scholar using relevant keywords, and only articles published since 2000 were included.

The review highlights the contribution of each modality to major forensic odontology applications such as human identification, age and sex determination, bite mark analysis, disaster victim identification (DVI), and postmortem examination. The transformative role of artificial intelligence and machine learning in automating workflows in dental identification is also discussed, along with existing limitations, including lack of standardization, inconsistency in digital dental records, and issues related to legal admissibility.

DICOM standards and the digital chain of custody are critically examined and their forensic implications are evaluated. The review concludes that digital imaging technologies represent the future of forensic odontology, with great potential to enhance identification accuracy and the reliability of judicial processes, provided that effective standardization programs and training systems are implemented across the Indo-Pacific region and beyond.

Keywords: Forensic Odontology; Digital Radiography; Cone Beam Computed Tomography; Disaster Victim Identification; Artificial Intelligence.

Introduction

Forensic odontology is a branch of dentistry that applies dental knowledge to the resolution of civil and criminal legal issues, particularly in the identification of deceased individuals, determination of biological parameters (age and sex) and analysis of bite mark evidence[1]. The field has a long history rooted in traditional radiographic techniques, which were once considered the gold standard for ante-mortem and post-mortem dental comparisons.

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However, the beginning of the twenty-first century has witnessed a dramatic transformation in diagnostic imaging across medicine and dentistry. The transition from analog to digital technologies has significantly enhanced image quality, processing capabilities and data compatibility. These advancements have profound implications for forensic odontology. Digital images can be transmitted across geographic boundaries in real time, enhanced using algorithms to reveal fine details, stored with complete metadata and matched with ante-mortem databases using sophisticated software platforms. These advantages are particularly valuable during mass casualty events and international DVI operations.

The Indo-Pacific region encompassing densely populated and disaster-prone countries in South Asia, Southeast Asia and Oceania presents unique challenges for forensic dentistry. Natural disasters such as tsunamis, earthquakes and cyclones frequently result in mass fatality incidents requiring rapid, accurate and scalable

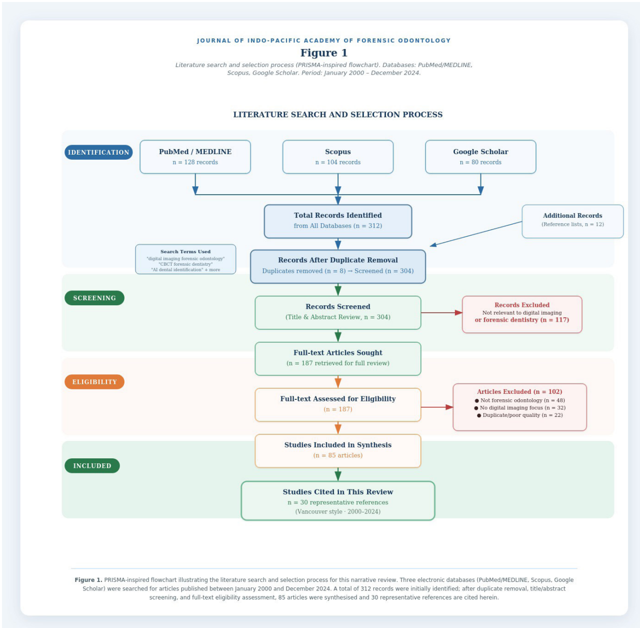

Figure 1: Flowchart of literature search and selection process (PRISMA-inspired). Databases: PubMed, Scopus, Google Scholar; Date range: 2000–2024; Total screened: 312; Final included: ~85]

identification methods. Digital imaging technologies offer a practical solution to these challenges.

Although a substantial body of literature exists on individual imaging modalities, there is a lack of comprehensive narrative reviews that integrate all major digital imaging technologies within forensic odontology. This review aims to address that gap by examining the full spectrum of applicable technologies, their forensic applications, and their limitations, thereby providing a valuable reference for practitioners and researchers.

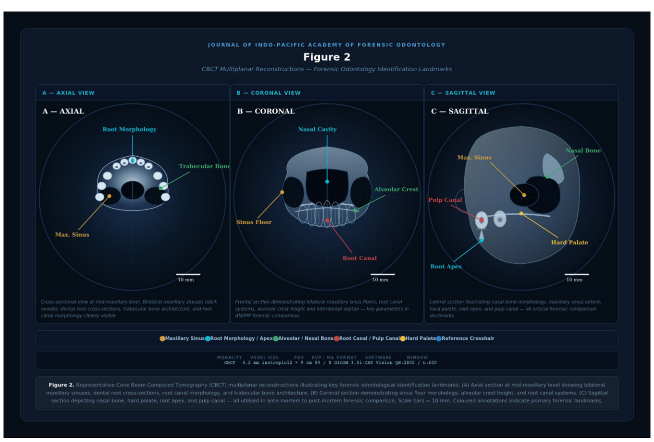

Figure 2: Representative CBCT reconstructions showing dental identification landmarks: (A) Axial, (B) Coronal, and (C) Sagittal views with annotated root morphology and trabecular bone patterns used in forensic comparison.

Methods

This study was conducted as a narrative review using a structured literature search strategy. Electronic databases, including PubMed/MEDLINE, Scopus, and Google Scholar, were searched for articles published between January 2000 and December 2024[4].

- The search terms included both individual keywords and combinations such as: digital imaging in forensic odontology, CBCT in forensic dentistry, digital radiography for dental identification, age estimation using virtual autopsy (dental), 3D scanning in bite mark analysis, virtual autopsy in dentistry, disaster victim identification imaging, forensic dental photography, and digital dental records in forensic science.
- Peer-reviewed original research articles, systematic reviews, review articles, and case reports were included if they specifically focused on the application of digital imaging in a forensic dental context and were published in English. Articles with non-English abstracts without translation was excluded.
- A total of 312 records were initially identified, of which 187 were excluded based on title and abstract screening. Following full-text review, 85 articles were deemed suitable for final synthesis. Thirty of the most representative references are listed below.
- Data synthesis was performed narratively and organized according to imaging modality, with critical appraisal based on clinical and forensic relevance.

Transition from Conventional to Digital Radiography in Forensic Dental Practice

Silver halide film was the main imaging modality, and the original approach in forensic odontology, which was used throughout more than a century before conventional dental radiography. The procedure is based on the individual arrangement of dental restorations, root morphology, the arrangement of trabecular bone and tooth shapes of the various teeth to make ante-mortem to post-mortem comparisons. Although this strategy has been able to facilitate significant number of identifications across the globe, it has been associated with intrinsic limitations such as time-consuming processing of films, vulnerability to image deterioration over times, inability to enhance the images made after collection and administrative problems of sharing images among the agencies .[1, 2,3,4]

Digital radiography It was developed in the 1980s and became widespread in dental practice during the 1990s and early 2000s and now changed these workflows essentially. The radiographic images are captured electronically and in the form of the Digital Imaging and Communications in Medicine (DICOM) format by direct digital sensor and photostimulable phosphor plate (PSP) systems. The DICOM standard does not just maintain the image alone but also other vital metadata such as acquisition parameters, date and times, patient identifiers and equipment details among

others which provide useful information to an evidentiary chain of custody .[3]

Table 1: Difference between conventional radiography and digital radiography

Parameter	*Conventional Radiography*	*Digital Radiography*
Radiation Dose	Higher; requires film processing chemicals	Up to 80% reduction in radiation exposure
Image Acquisition Time	Minutes (film development required)	Seconds; immediate display on monitor
Image Enhancement	Not possible post-capture	Contrast, brightness, zoom adjustable digitally
Storage	Physical storage; susceptible to damage and degradation	Electronic; DICOM format; cloud-compatible
Transmission	Physical transport only	Instant electronic transfer; tele-forensic use
Forensic Comparison	Manual overlay; laborious and subjective	Software-aided superimposition; objective
Cost	Low initial cost; ongoing film/chemical costs	Higher initial investment; lower running costs
Legal Admissibility	Accepted but difficult to reproduce precisely	Metadata ensures integrity; DICOM provides audit trail

The main forensic benefits of digital radiography compared to conventional film are reduced radiation dose by up to 80 percent, instant availability of images, dynamic post-processing software, e.g. contrast control and magnification and compatibility with forensically oriented software platforms e.g. WinID and DVI System International .[4] Electronic transmission of images among forensic work forces across borders has found its way and is really useful in multinational identification processes. Table 1 is a comparative overview of both modalities in terms of parameters that are of forensic concern.

Cone Beam Computed Tomography (CBCT) in Forensic Odontology

Cone beam computed tomography (CBCT) is one of the most significant developments in dental imaging over the past decades. CBCT can be used as a replacement for conventional computed tomography (CT) because, compared to the latter, it uses a cone-shaped X-ray beam and a two-dimensional detector to produce three-dimensional volumetric data of the dentofacial complex at a significantly lower radiation dose and cost. CBCT has been widely applied in forensic odontology across a range of investigative applications .[5,6]

CBCT relies on the unique three-dimensional morphology of dental and craniofacial structures for human identification. It has been observed that maxillary sinus patterns, frontal sinus shapes, trabecular bone architecture, and dental root structures obtained through CBCT serve as useful biometric markers .[6] Image registration algorithms can be used to match ante-mortem and post-mortem CBCT datasets, offering a level of precision significantly higher than that of two-dimensional projections. In the absence of ante- mortem CBCT datasets, traditional periapical or panoramic radiographs can still be compared with post-mortem CBCT reconstructions by generating two-dimensional representations from the three-dimensional volume.

CBCT is also highly valuable in age estimation, which is a critical parameter in the investigation of unidentified remains. Third molar development, root formation, and pulp cavity dimensions can be accurately measured using this modality in three dimensions. Approaches based on pulp- to-tooth volume ratios derived from CBCT data have been shown to correlate well with chronological age in several population studies .[7, 8] Sex estimation is also enhanced, and CBCT-based linear and volumetric measurements of the condyle, ramus, and symphysis dimensions of the mandible allow discriminant function analyses with acceptable levels of accuracy .[9]

CBCT can also be used in cases of trauma and bite mark analysis to accurately document injury patterns and match them with dental casts or computer-generated images of a suspect. The ability to image the entire dentition and supporting structures rapidly, without disturbing fragile or decomposed remains, has led to the incorporation of post- mortem CBCT into international disaster victim identification (DVI) protocols due to its capacity to depict dentition and surrounding structures within a single imaging system .[9]

Intraoral and Extraoral Digital Imaging Systems

Intraoral digital radiography, using charge-coupled device (CCD) or complementary metal-oxide semiconductor (CMOS) sensors, provides high-resolution periapical and bitewing images essential for detailed comparison of dental structures. These sensors offer spatial resolution superior to conventional film and deliver radiation doses as low as 13 micro Sieverts per exposure.[11] In forensic investigations, periapical radiographs remain the cornerstone of ante- mortem and post-mortem comparisons, as they reveal specific details of root morphology, canal configuration, and restoration margins[5,6].

Panoramic digital radiography, also known as digital orthopantomography (OPG), produces a single extraoral image of the entire dentition, mandible, and maxilla. Digital OPGs are invaluable in forensic settings as they facilitate mass screening, dental profiling of unidentified remains, and age estimation based on stages of dental development. Several age estimation methods, including Demirjian's 8-tooth method, Willems' modification, and the London Atlas, have been applied using digital OPGs and validated across diverse populations.[10,11]

Digital lateral cephalometry, commonly used in orthodontics, has also found applications in forensic science,

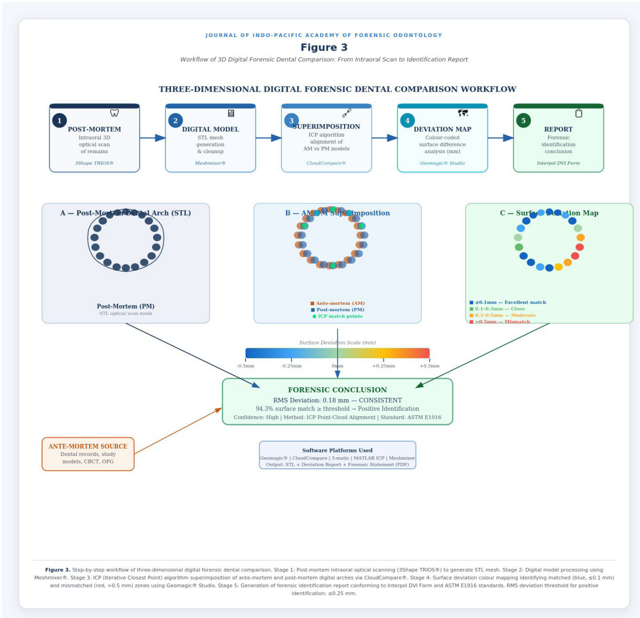

Figure 3: Workflow diagram of 3D digital forensic dental comparison: (A) Intraoral scan of post-mortem dentition, (B) Superimposition with ante-mortem model, (C) Deviation colour map indicating matched and unmatched regions.

particularly in craniofacial superimposition and identification of unknown skulls through comparison with ante-mortem photographs or radiographs. The digital format enables precise identification and measurement of anatomical landmarks, making cephalometric analysis more objective and reproducible compared to traditional film-based methods.

Digital Dental Photography in Forensic Documentation

Digital photography is an indispensable component of forensic dental documentation. High-resolution digital single-lens reflex (DSLR) cameras equipped with ring flash units enable the capture of standardized and reproducible clinical images of dental arches, individual teeth, soft tissue injuries, and bite marks. Such photographic documentation serves as primary evidence and supports both physical and radiographic findings.

Digital photography has significantly improved the documentation of bite mark evidence, a historically controversial area in forensic odontology. Subtle tissue markings, often not visible to the naked eye, can be enhanced using techniques such as two-dimensional photographic overlays, color channel analysis, and luminescence visualization with alternate light sources. [16] Image analysis software enables objective comparison of bite mark patterns with dental models of potential suspects, generating measurable similarity indices rather than relying solely on qualitative assessment.

Adjunctive forensic techniques such as cheiloscopy (study of lip print patterns) and palatoscopy (analysis of palatal rugae patterns) are supported by high-quality digital photography for accurate capture and comparison. Digital systems facilitate efficient storage and retrieval of such records for future reference. Although these techniques are not independently validated for definitive identification, they serve as useful complementary tools .[12,13]

Three-Dimensional Scanning and Photogrammetry in Forensic Dentistry

Three-dimensional (3D) optical scanning has revolutionized the recording and evaluation of physical dental evidence. Laser scanners and structured light scanners can capture

the surface geometry of dental arches, bite marks, and dental models with micron-level accuracy. The resulting digital mesh files allow direct comparison with post-mortem dental impressions or CBCT-derived surface models using proprietary or open-source point-cloud alignment software[18]

The application of 3D scanning in bite mark analysis addresses a key limitation of traditional two-dimensional methods, namely the inability to capture surface depth and topography. By recording both the surface contours of bite marks and the dentition of suspected individuals, digital alignment and superimposition can be performed with enhanced geometric precision, reducing errors due to distortion or misalignment.Validation studies using porcine skin models and silicone substrates have demonstrated that 3D bite mark analysis offers significantly higher specificity compared to conventional 2D overlay techniques[12,13,14].

Close- range photogrammetry, which involves reconstructing three-dimensional measurements from multiple overlapping two-dimensional photographs, provides a cost-effective alternative to dedicated 3D scanners. Accurate 3D models of crime scene evidence, dental arches, and skeletal remains can be generated using standard digital images and software platforms such as Agisoft Metashape or Open MVS. This approach increases accessibility of advanced imaging techniques for forensic practitioners without requiring expensive specialized equipment .[13,14,15]

Artificial Intelligence and Machine Learning in Forensic Dental Imaging

The application of artificial intelligence (AI) and machine learning (ML) to digital dental imaging represents one of the most rapidly advancing areas in modern forensic odontology. In particular, deep learning algorithms, especially convolutional neural networks (CNNs), have demonstrated significant potential in automated dental feature detection, age estimation, sex determination and record matching tasks[16].

CNNs trained on large datasets of panoramic radiographs have achieved age group prediction accuracies of up to 90% in adult populations and have shown applicability across diverse ethnic groups. These systems can simultaneously analyze multiple dental features—such as root development stage, cementum deposition, secondary dentin formation and pulp chamber reduction—which would otherwise require considerable time using manual methods. Importantly, AI-based age estimation systems offer

Table 2: Summary of AI and Machine Learning Technologies in Forensic Dental Imaging

AI Technology	*Application in Forensic Dentistry*	*Reported Accuracy / Outcome*	*Key Limitation*
Convolutional Neural Network (CNN)	Dental age estimation from OPGs	>90% accuracy in adult age estimation	Population-specific training required
Deep Learning (ResNet/VGG)	Automated tooth segmentation and numbering	95% sensitivity in panoramic radiographs	Performance drops with poor image quality
Machine Learning (SVM, Random Forest)	Sex estimation from crown/root dimensions	Up to 85% classification accuracy	Requires large training datasets
NLP + Computer Vision	Automated dental record matching in DVI	Reduced identification time by ~60%	Dependent on quality of ante-mortem records
AI-assisted Bite Mark Analysis	Pattern recognition in bite mark evidence	Promising; reduces examiner subjectivity	No validated standardised protocol yet

examiner-independent and reproducible results, making them more suitable for judicial evaluation compared to subjective expert assessments[17].

In post-mortem dental identification, AI-based matching algorithms are used to compare digital dental records—including radiographs, charts, and clinical notes—with ante-mortem databases to generate a shortlist of potential matches. Studies indicate that these systems can reduce identification turnaround time in disaster victim identification (DVI) operations by up to 60% compared to manual methods. Additionally, natural language processing (NLP) techniques have been employed to extract structured data from unstructured ante-mortem dental records, thereby enhancing database searchability.

Machine learning–based sex estimation methods using mandibular measurements derived from CBCT or OPG have demonstrated classification accuracies ranging from 80% to 85% across multiple population studies. Although these methods are not sufficiently accurate for definitive individual

identification, they serve as valuable screening tools during the triage of unidentified remains.[16,17] A summary of major AI technologies and their applications in forensic dental imaging is presented in Table 2.

Virtual Autopsy and Post-Mortem Dental Imaging

Virtual autopsy, also known as Virtopsy, is a post-mortem examination technique in forensic pathology that utilizes non-invasive imaging modalities—primarily multi-detector computed tomography (MDCT) and magnetic resonance imaging(MRI)—as a supplement or alternative to traditional autopsy .[25] In forensic odontology, whole-body MDCT scans acquired during Virtopsy procedures generate three- dimensional volumetric images of the entire dentofacial complex, including teeth, alveolar bone, mandible, maxilla and associated soft tissues[18].

Virtopsy-based MDCT scans can be used for dental identification, trauma assessment, and age estimation. Segmentation software enables the creation of isolated three-dimensional reconstructions of the dentition, which

can then be compared with ante-mortem radiographic records. Studies comparing dental data obtained through Virtopsy with conventional post-mortem dental charting have demonstrated high concordance in identification outcomes, indicating its potential as a primary identification method in mass casualty incidents where invasive examinations may be logistically impractical.

The integration of Virtopsy data with national and international forensic databases, such as INTERPOL's disaster victim identification (DVI) systems, is an area of ongoing development. Standardized MDCT datasets in DICOM format ensure data integrity, enable remote access, and support cross-platform interoperability, making them particularly valuable in multinational identification efforts, especially in regions such as the Indo-Pacific.[1,2,19,20].

Digital Evidence Management and Chain of Custody

Digital dental images possess significant evidentiary value; however, their admissibility depends on maintaining the integrity of the chain of custody, which involves a documented and continuous record of possession, handling, and transfer of evidence from the time of collection to its presentation in court. Images stored in DICOM format include metadata such as the date and time of

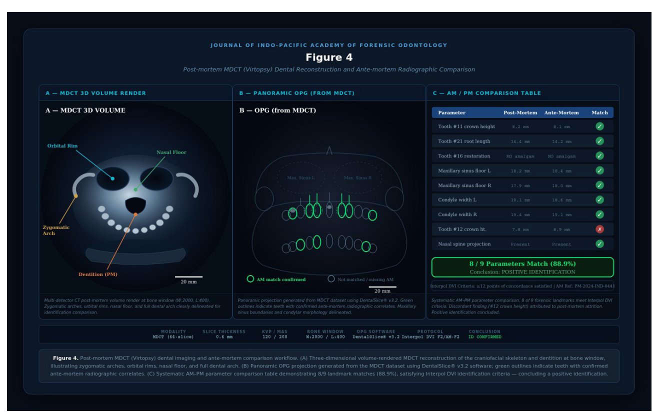

Figure 4: Post-mortem MDCT (Virtopsy) dental reconstruction (A) Volume-rendered 3D view of dentition, (B) Corresponding orthopantomograph projection generated from CT data, (C) Overlay comparison with ante-mortem panoramic radiograph for identification.

acquisition, equipment identifier, operator, and institution, thereby providing an auditable trail that ensures evidentiary integrity.[20]

Software platforms designed for forensic dental record management—such as WinID3, UDIM (Universal Dental Identification Module), and PLASS DATA V-International—facilitate the management of DICOM-compliant images alongside dental charts and written records. These systems enable systematic comparison of ante-mortem and post- mortem data, generation of formal identification reports, and maintenance of the chain of custody throughout the identification process.

Digital dental evidence is not legally recognized in all jurisdictions. However, evolving legal frameworks in India and other Indo-Pacific countries, including the Information Technology Act, 2000, are increasingly supporting the admissibility of electronically generated and stored records, provided their authenticity can be established. Techniques such as hash verification, digital signatures, and secure storage mechanisms are essential for maintaining data integrity. Therefore, forensic odontologists must be familiar with jurisdiction-specific legal requirements to ensure the admissibility of digital evidence .[20]

Limitations and Challenges

Despite the transformative potential of digital imaging technologies in forensic odontology, several significant limitations remain. One major challenge is the lack of standardized ante-mortem digital dental record systems in many developing countries within the Indo-Pacific

region. Since comparative identification relies heavily on ante-mortem records, their absence, poor quality, or incompleteness represents a critical barrier to successful identification in mass fatality incidents.[1,8,9,10]

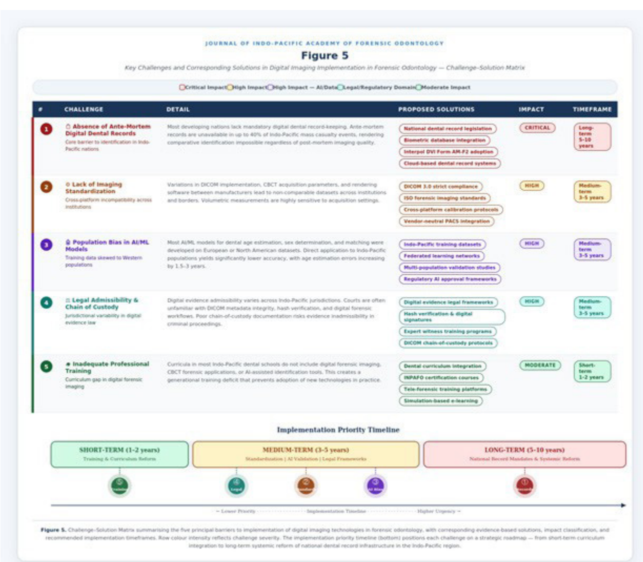

Figure 5: Schematic summary of key challenges in implementing digital imaging in forensic odontology: Standardization gaps, ante- mortem record availability, AI bias, legal admissibility, and training deficits — organized as a challenge-solution matrix.

Another key issue is the lack of standardization across digital imaging platforms. Variations in image acquisition parameters, differences in DICOM implementation, and inconsistencies in manufacturer-specific software rendering can limit the comparability of images obtained from different systems unless they are calibrated according to standardized protocols. This issue is particularly relevant for CBCT and three-dimensional scanning modalities, where volumetric measurements are highly sensitive to acquisition settings .[1,7,16,20]

Challenges related to artificial intelligence (AI) include training data bias, population specificity, and regulatory approval. Many AI models have been trained on datasets derived from specific geographic or ethnic populations, limiting their generalizability to the diverse populations of the Indo-Pacific region. Furthermore, the absence of standardized, peer-reviewed validation frameworks for AI-based forensic dental tools raises concerns regarding their admissibility in court. Ethical considerations also arise from the increasing reliance on automated systems without adequate human expert supervision.

Future Perspectives

Digital imaging in forensic odontology holds significant potential for future advancements. The integration of digital dental records with national biometric identity databases— including fingerprint, iris and DNA datasets—represents a

paradigm shift toward multimodal forensic identification systems that are more robust and reliable. In countries with Aadhaar-based health records or similar systems, the availability of ante-mortem dental data for post-mortem identification is an achievable near-term objective.[6,19,20]

Online forensic dental identification platforms could enable real-time sharing of post-mortem dental data among investigators and international agencies, thereby significantly reducing identification time in mass disaster scenarios. When combined with AI-based automated matching systems, these platforms have the potential to transform disaster victim identification (DVI)[21] operations from prolonged manual processes into efficient workflows that can be completed within hours. Another promising development is tele-forensic odontology, which involves remote consultation with forensic experts using digital imaging and has the potential to extend specialized expertise to underserved regions.

Mixed reality and augmented reality technologies offer new opportunities in forensic dental education and courtroom evidence presentation. Augmented reality overlays of comparative dental data on craniofacial reconstructions could provide juries and judges with intuitive visual representations, thereby enhancing understanding of identification processes. Furthermore, the development of globally accepted standards for digital forensic dental records, similar to INTERPOL's DVI guidelines, is an urgent priority for the international forensic odontology community[24].

Conclusion

The advent of digital imaging technologies has transformed the field of forensic odontology, enabling capabilities that were previously unattainable with conventional radiographic methods. From the advantages of digital periapical radiography—such as reduced radiation exposure, immediate image availability, and enhanced software-based analysis—to advanced three-dimensional imaging modalities such as CBCT, 3D scanning, and virtual autopsy, the discipline is undergoing a significant technological evolution. The future integration of artificial intelligence is expected to further revolutionize forensic dental practice[19,20].

The adoption and standardization of digital imaging technologies are not only scientific imperatives but also humanitarian necessities, particularly in the Indo-Pacific region, where mass disaster incidents are frequent and ante-mortem dental record infrastructure remains underdeveloped. To translate technological advancements into effective forensic outcomes, investment in professional training, digital record management systems and inter- agency data-sharing frameworks is essential.[23]

Forensic odontology stands at a critical intersection of science, technology, and law, where strengthening the digital evidence base will enhance the reliability of identification processes. With continued advancement and standardization, it is conceivable that every digital image— every pixel—may one day serve as reliable forensic evidence.[24]

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