Revolutionizing Forensic Odontology: The Integration of 3D Scanning and AI for Enhanced Identification Processes

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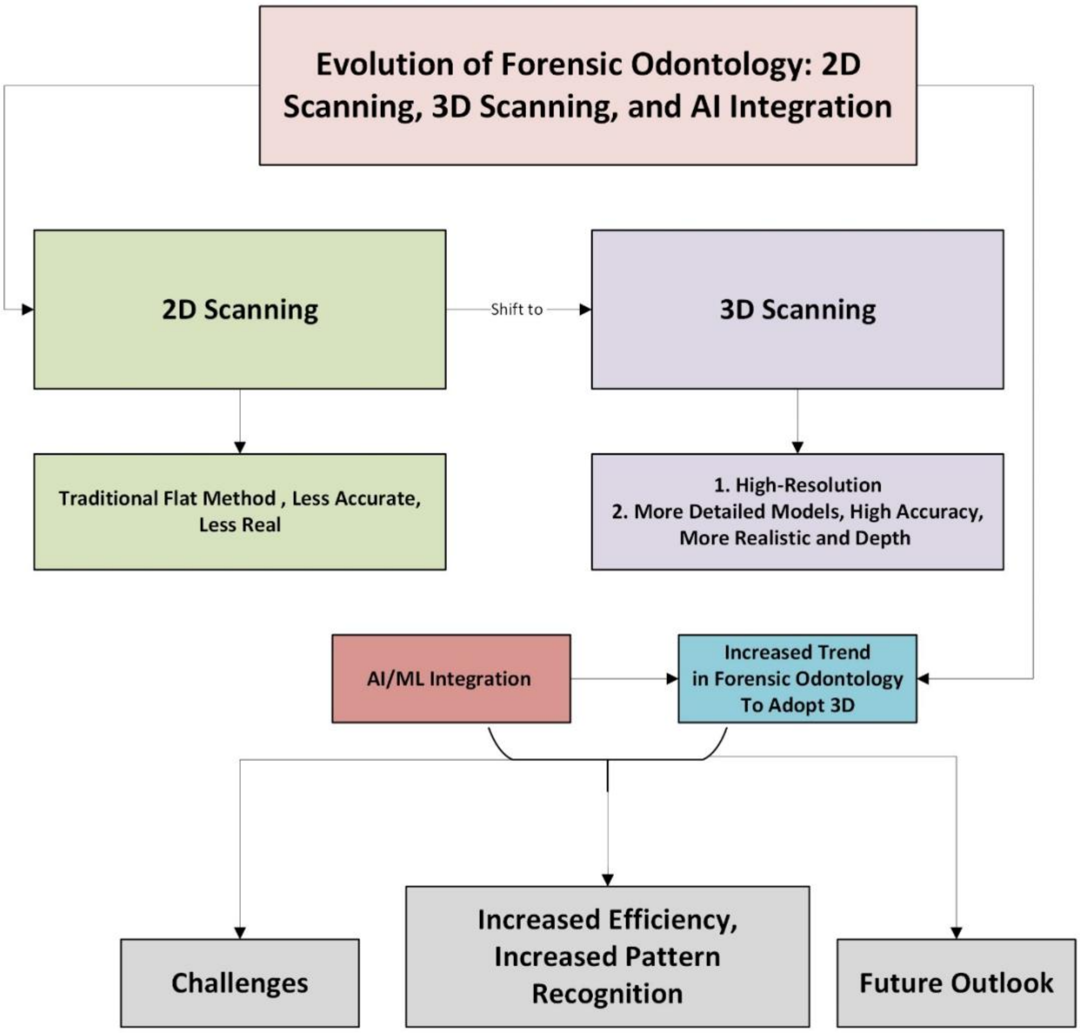
Received: 17-12-2024, **Accepted:** 29-12-2024, **Published online:** 20-01-2025

Abstract

Nowadays, most forensic odonatological analyses destined for legal purposes include improvements in 3D scanning technologies with the aim of enhancing the precision of forensic identifications. The current paper addresses the combination of 3D picture scan data and artificial intelligence: it reviews uses, limitations, and prospects of AI in its application to forensic odontology. Where earlier methods were limited, 3-D scanning techniques allow the creation of much more realistic models of dental structure, enabling closer comparisons with dental records and other information. These technologies, when combined with artificial intelligence, can even automate such processes as pattern recognition, further speeding up the reliability of dental identification in forensic cases. Not all is perfect with the technology. Further, defects in the models generated may well be caused by external reasons such as lighting, movement during scanning, and equipment limitations. Besides this, 3D photo's scanning using AI effectively requires highly knowledgeable people in advanced hardware and software technologies. As a matter of fact, the intricacy at which AI algorithms are designed demands an in-depth knowledge of their implementation to effectively apply them in forensic activities. Apart from this, constant system calibration and the care in handling scanning equipment are also needed to ensure accuracy and reliability. If these tools work effectively, AI coupled with 3D photo scanning can do much to increase the accuracy, efficiency, and rapidity of forensic odontology, particularly identification cases. The growing corpus of research findings and breakthroughs in technology, despite such challenges, portend a bright future for the application of AI and 3D scanning in the field of forensic odontology, opening the door for improved forensic techniques and methodologies of identification. This review discusses such breakthroughs, obstacles, and the potentiality for wide application of these technologies in the near future.

Keywords: Forensic odontology, 2D images ,3D images, AI, dental Investigation.

Graphical Abstract



Introduction

Over time, dental procedures for forensic human identification have consistently proven to be highly useful and reliable. If precise and comprehensive dental data obtained before death are accessible, which are necessary for a definitive identification, this can be accomplished. In field of forensic odontology, many specific dental data coding systems have been created for the purpose of utilising them in reports and computer-assisted identifications (Reesu *et al.*, 2020).Forensic odontology (FO), according to Keiser-Neilson, is the "branch of forensic medicine that, in the interest of justice, deals with the proper handling and examination of dental evidence as well as the proper evaluation and presentation of the dental finding. A subdivision of forensic medicine is referred to as forensic odontology, is widely recognised as a reliable and cost-effective scientific method for identifying individuals in the aftermath of mass disasters (MDs), alongside cases involving crimes and accidents(Dong et al., 2022). Forensic dentistry, also known as forensic odontology, is one of the three main identifiers acknowledged by Interpol for victim identification in mass casualty events or Mass disaster. Forensic dentistry is the field that examines the intersection between dentistry and the legal system. The utilisation of various digital radiographs and photographs using scanning techniques is essential for the clearance process in the domain of forensic dentistry (Yazdanian et al., 2022). Radiographs are commonly used in clinical practise, and both intra-oral and extra-oral X-ray examinations are essential for diagnosis and planning treatment. In addition to the dental charts and written notes, the patient record contains photographs. Comparing one set of records to another is a crucial aspect of forensic dental investigation. This method requires for use of the radiological images, which depict how the teeth and facial tissues appeared at a specific moment. This method of determining a person's stage of development for identification or other legal purposes, such as determining their age for criminal sentence or immigration, can be done using dental x-rays. Additionally, it can be utilized in judicial investigations to look for tooth and facial damage(Viner & Robson, 2017).Determining a person's age and gender using forensic dentistry mainly relies on the identification approach provided by conventional radiography. The field of forensic dentistry makes use of a wide variety of radiographic pictures, such as panoramic radiographs, cephalometric radiographs, lateral and oblique radiographs, and intraoral periapical radiographs. During the past few years, there has also been an increase in the usage of digital radiographs, which are utilized to differentiate between premortem images obtained from dental offices and centres and post-mortem radiographic photographs that are employed for independent recognition (Kukade et al., 2022).

Radiographs of the dentition are vital components of dental records and play a pivotal role in the process of ascertaining an individual's identity. Several research suggestions have been put forward in the past two decades for the development of semi-automatic (Chen & Jain, 2005; Jain & Chen, 2004) and automatic (Banday & Mir, 2018) dental identification procedures using two-dimensional (2D) radiographs. However, methods based on 2D radiography had several shortcomings. The process of tooth segmentation required a lot of time and produced inaccurate data due to the low image quality brought on by blurring dental radiographs. The retrieval and recognition of 2D radiography in an automated manner can provide challenges due to the substantial alterations in tooth shape and arch that may arise from different imaging perspectives (Arunkumar et al., n.d.; L. Wang et al., 2020).

To overcome the inherent constraints of 2D-based approaches, it is crucial to develop a functional and efficient automated 3D dental identification system that would improve the identification process. The utilisation of three-dimensional (3D) imaging in the field of dentistry has experienced a substantial surge in recent years. This is leading to the transformation of clinical practises and laboratory procedures into digital workflows(Pitta, 2019).An alternative to using traditional imprint materials, the development of intra-oral scanners allows for the direct digitalization of a patient's dental arches (Naidu & Freer, 2013; Ting-shu & Jian, 2015). The process of utilising a laser scanner allows for the conversion of dental casts into 3D models. This digital system provides numerous significant benefits, such as decreased impression time, decreased patient burden, improved storage and retrieval efficiency, enhanced accuracy, immediate access to 3D diagnostic information, and convenient portability of digital data (Chalmers et al., 2016; Wesemann et al., 2017) . These models can subsequently be used for alignment and matching, as well as for an automated study of comparable dental structures (Martin et al., 2015). However, 3D photo scan data in forensic odontology also poses some challenges including Data Quality and Resolution, Variability in

Anatomical Structures, Segmentation and Reconstruction Issues and Integration with Other Data Types.

Literature review

The emerging role of 3D printing in forensic odontology, a technology that transforms digital models into physical objects. It identifies key applications, including bite mark analysis, dental age estimation, gender identification, facial reconstruction through 3D computed tomography, and physical modeling. While the paper provides useful insights into the benefits of 3D printing, it stresses the importance of further research to evaluate its precision, consistency, and to develop standardized protocols for its application in forensic odontology [29].

By merging 3D scan data with photogrammetry software, this method facilitates the precise alignment of AM (ante-mortem) and PM (post-mortem) images, enhancing forensic identification accuracy. The study analyzes a range of 3D imaging tools, highlighting their advantages and drawbacks. A noteworthy development, the Combined Holding and Aiming Device (CHAD), was created with 3D printing to address alignment issues in forensic dental imaging. This device, along with the Modified External Aiming Device (MEAD), was assessed in comparison to other devices, specifically for error rates in radiographic exposure of PM intraoral periapical images. Both CHAD and MEAD achieved low positioning errors without exposing participants to ionizing radiation. Nonetheless, the study acknowledges that more extensive validation is needed due to its small sample size, suggesting that innovations like CHAD could significantly improve the accuracy of AM-PM image alignment and victim identification. [17].

Forensic facial reconstruction (FFR) plays a critical role in identifying unknown remains by reconstructing facial features from skull structures, aiding in potential identification. Technological advances, particularly in open-source software, have made FFR more affordable and accessible. This study outlines a protocol using tools like PPT GUI for 3D scanning, MeshLab for point cloud processing, and Blender for creating facial models and textures, all of which depend solely on digital cameras. The procedure supports both forensic and research contexts, making it versatile [18].The integration of medical imaging with rapid prototyping offers an innovative approach to developing 3D models of anatomical structures for forensic purposes. Techniques such as computed tomography (CT), CT angiography, MRI, and photogrammetry allow researchers to create detailed 3D polygon meshes. These meshes can then be transformed into color-enhanced models that highlight specific pathologies, including bone fractures, vascular ruptures, heart infarctions, and injuries like bite marks. Such anatomically accurate and fully colored models enhance forensic analysis by providing clear, tangible representations of evidence, which is invaluable for investigations, educational applications, and legal proceedings[19].The Utilizing computer-aided design (CAD) and 3D printing technology in medical reconstruction offers significant advantages for patients with craniofacial abnormalities. CAD facilitates precise planning and customization of surgical templates and implants, aligning them with the unique skeletal structure of each patient. Coupled with CT imaging, this technology allows for the creation of accurate physical models, such as implant prototypes or skull replicas, through methods like CAM/CNC and rapid tooling. This integrated approach improves surgical preparation, enhances visualization, and provides patient-specific solutions that minimize operative errors and reduce procedure time, ultimately streamlining craniofacial reconstruction [20].

Digital radiography and photographs of pulverised tooth fragments were both included in the activities that assessed one's capacity to estimate another person's age. In addition, computerised measurement instruments and tables categorised by age groups were used. PM results were matched to the AM data using the Interpol standard, and thereafter an analysis was conducted. This comparison and reconciliation were all part of the process of identifying the body. Some of the contributions that can be made because of this study are as follows:

1. The supply of digital educational resources in "forensic odontology", including "dental identification" following numerous deaths and dental age estimate across various age cohorts.

2. Demonstrating the use of electronic patient records, which include "intraoral scans" of the teeth, "digital radiographs", pictures, and written records of dental treatment.

3. Implementing a hybrid instructional method that can be carried out in its entirety online.

4. Making available an efficient resource that can encourage and engage students in the activity of expanding their interest and knowledge of the topic at hand

.5. Utilising the newly available opportunities presented by digitalization and intraoral scanning in the field of forensic odontology [21].3D printing technology in dentistry has transformed the creation of dental appliances such as models, restorations, and surgical guides. The process begins by capturing data from intraoral optical scanners and cone beam computed tomography (CBCT). This data is then converted into a standard tessellation language (STL) format, which is further refined in 3D modeling software. The use of this technology improves the precision of dental treatments, reduces costs, and speeds up the overall process. By enabling more accurate, efficient, and accessible procedures, 3D printing has become a game-changer in modern dental practices. [22].The ability to visualize osteological evidence in court is crucial, particularly with the use of advanced 3D imaging techniques like MRI, CT scans, and surface scanning. These methods provide a more precise and detailed representation of evidence compared to traditional 2D images, facilitating a deeper analysis that can be pivotal in determining the cause of death. Moreover, 3D imaging can reduce the emotional burden by eliminating the need for graphic autopsy photographs and presenting the evidence from multiple angles. Despite these advantages, the use of 3D digitization also brings challenges, such as the need for accurate reconstructions of crime scenes and a lack of standardized practices in forensic settings [24].The role of 3D printing in forensic medicine and pathology through an extensive review of existing literature. It highlights the various ways in which 3D printing is currently applied, such as for reconstructing injuries, comparing injuries with weapons, and enhancing evidence presentation in legal contexts. The technology is also recognized for improving anatomical modeling, facilitating better communication among forensic experts, and serving as a tool for education. However, the adoption of 3D printing in forensic medicine faces challenges, including high costs, the need for specialized equipment, and time-consuming processes [25]. The use of 3D printing in forensic odontology, specifically in creating accurate replicas of human teeth for forensic purposes. The research involved five different 3D printing methods: FDM, SLA, DLP, PolyJet, and SLS, which were tested using models of extracted teeth. The results demonstrated that the printed replicas matched the original teeth within a margin of 0.5 millimeters, with Digital Light Processing (DLP) being the most precise method for forensic applications [26]. The combination of smartphone cameras and monoscopic photogrammetry for 3D bitemark analysis holds significant promise in forensic investigations. This approach could offer a low-cost, accessible alternative to traditional methods. Forensic odontology utilizes the unique features of an individual's dental impression to match bite marks to potential perpetrators. However, various factors such as the force of the bite, tooth morphology, and the quality of the images can influence the precision of this analysis. The integration of smartphone technology and photogrammetry presents a promising solution to these challenges, though further research is needed to validate its effectiveness and accuracy in forensic contexts [27]. the use of high-quality smartphone selfies as ante-mortem (AM) data in forensic dental identification, particularly when traditional dental records are missing. The study compares selfies to 3D post-mortem (PM) scans using two techniques: 2D visual comparison and 3D superimposition. The results show that 3D superimposition significantly improves the accuracy of matches, achieving a 94.2% success rate in correctly rejecting mismatches, compared to a lower 77% accuracy using 2D methods. This suggests that selfies, when combined with advanced 3D techniques, could serve as a reliable alternative for AM data in forensic identification [36].Additionally, AI is the backbone of analysing 3D data, especially in dental record administration and forensic data analysis. In this regard, IDIS uses intelligent pattern recognition techniques to computerize the dental record matching process and considerably enhance identification accuracy in forensic scenarios. IDIS consolidates methods and algorithms of identification that make possible the analysis of huge dental records, which are indispensable in forensic odontology. It enhances the traditional dental record using odontogram, which are visual representations of dental features to thereby enable automated comparisons. Besides that, AI-powered dental image analysis utilizes 3D scans in anomaly detection and effective management of patient records, hence indicating the importance of automatic feature extraction in the interpretation of data. The identification process is accelerated by the integration of AI technology in forensic investigations due to the increased levels of accuracy, therefore becoming an indispensable tool in contemporary dentistry and forensic sciences today (Chomdej et al., 2006).AI-based techniques are transforming forensic investigations related to the detection and matching of tooth patterns. Machine Learning is employed intensively to analyse big dental datasets, increasing the accuracy and speed of identification and matching dental records with unidentified remains. Their major focus is on the identification of salient features within the dental structures, highly essential for forensic odontologists, mainly in tooth arrangement and morphology. The automated dental identification system uses artificial intelligence in the matching process and considerably speeds up forensic investigations with greater speed and accuracy(Abdel-Mottaleb et al., 2003). This is further enhanced by the inclusion of pattern matching algorithms that permit the comparison of dental patterns from different sources-a fundamental identification of identity and evidence required for lawsuit purposes. In total, all these AI-powered technologies constitute a serious breakthrough in forensic analysis, enabling methodologies to identify cases so much more accurately and faster in complexity(Abdel-Mottaleb et al., 2003).

Table 01: Comparison of Traditional vs. 3D Photo Scan Methods in Forensic Odontology

Criteria	Traditional Methods	3D Photo Scan Methods
Accuracy	Moderate (dependent on plaster casts, etc.)	High precision (down to millimeters)
Data Storage	Physical models and 2D records	Digital, easy to store and share
Reproducibility	Limited	Highly reduceable
Cost	Lower	Higher initial investment
Time efficiency	Slower, manual comparisons	Faster, automated with AI integration
Non-invasiveness	Invasive (plaster models, X-rays)	Non-invasive, digital scan
Portability	Non-Portable	Digital format, easily transferable

Table 01 Depicts the comparison of traditional vs. 3D photo scan methods in forensic Odontology

The report indicates several technological challenges that relate to the application of 3D-scanning technologies, one of which is the multi-camera device "Botscan," for the documentation of injury in forensic investigations. Among the most relevant challenges, the price of the complicated Photobox system-which features 70 cameras and several light panels-is out of reach of most forensic departments. Further, the stationary nature of the device means it is limited to subjects who can physically reach the scanning area; thus, eliminating seriously injured individuals. The usefulness of the device relies on appropriate illumination and subject posture, which is vulnerable to impairment should the former conditions be bad. It is also in posture and clothing that the scan can be interfered with since the latter masks the injuries, and essential postures are not feasible practically for a lot of people. Lastly, although 3D models have visual representations, they cannot replace tests done physically which would distinguish between kinds of damage; hence, 3D documentation is a priceless tool but by no means a flawless alternative for traditional forensic procedures. These limitations underpin the need for further research and development in raising the integration of current 3D technology within forensic practice(Sieberth et al., 2020).

Table 02: AI Tools Used in Forensic Odontology

AI Tool/Algorithm	Application Area	Advantages	Challenges
Machine Learning Models	Dental pattern matching	Faster and accurate	Requires large datasets
Deep Learning Algorithms	Bite mark analysis	High precision	Computationally expensive
Neural Networks	Age estimation from dental data	Can process complex data patterns	Prone to overfitting in small datasets
Image Recognition Systems	3D photo scan comparison	Automated analysis, large-scale capability	Dependent on high-quality input data

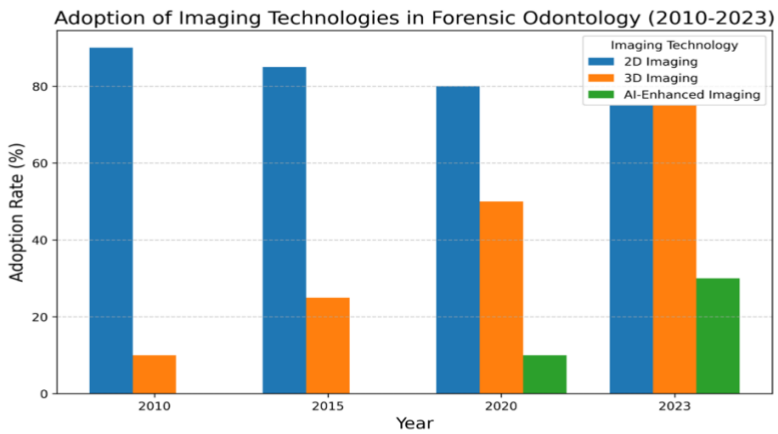
Three-dimensional convolutional neural networks (3D CNNs) represent a powerful application of artificial intelligence (AI) in image processing and recognition, leveraging deep learning to handle both generative and descriptive tasks. Unlike traditional models, CNNs have the ability to autonomously identify key features from data without human intervention. The unique strength of 3D CNNs lies in their capacity to process three-dimensional data, such as 3D volumes or a series of 2D images, like slices from a cone-beam computed tomography (CBCT) scan. The primary aim is to foster collaboration between forensic medical experts and AI engineers, enabling professionals with basic knowledge of AI to implement it in forensic research. This paper presents a new workflow for applying 3D CNNs to analyze full-head CBCT scans, exploring its potential in five forensic research areas: (1) sex determination, (2) biological age estimation, (3) 3D cephalometric landmark annotation, (4) growth vector prediction, and (5) facial soft-tissue estimation from skull data. Ultimately, the integration of 3D CNNs could revolutionize forensic medicine, significantly improving analysis workflows through advanced neural network technology (Thurzo et al., 2021). The use of two convolutional neural networks (CNNs), VGG16 and ResNet101, for estimating dental age (DA) within an eastern Chinese demographic. We utilized a dataset comprising 9,586 orthopantomograms (OPGs), which included 4,054 boys and 5,532 girls aged between 6 and 20 years. The performance of both CNN models was assessed using various metrics, including accuracy, recall, precision, and F1 score. The findings revealed that VGG16 surpassed ResNet101 in overall performance, achieving a remarkable accuracy of 93.63% for the 6-8 age group. This suggests that VGG16 has significant potential for application in both clinical settings and forensic investigations related to DA estimation. This version retains the essential information while using different phrasing to ensure originality (J. Wang et al., 2023).

Table 03: Prospective Future Applications of 3D Photo Scanning and AI in Forensic Odontology

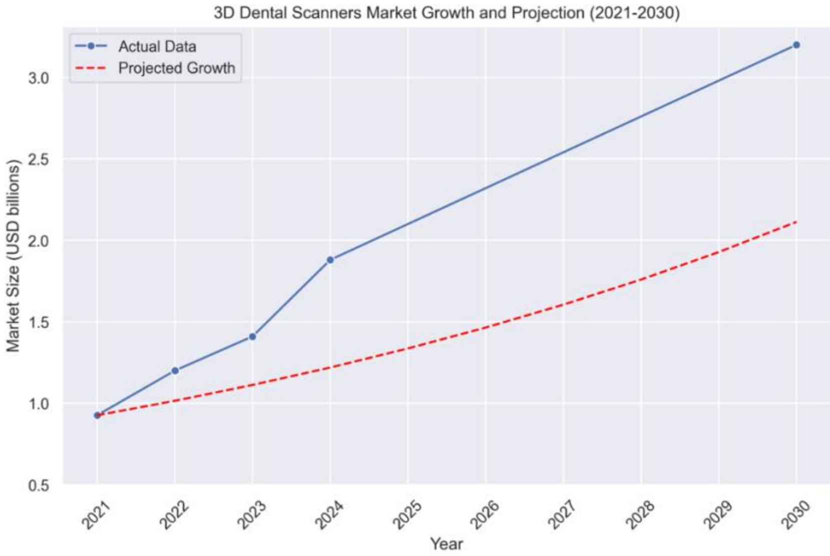
Application Area	3D Photo Scan Role	AI Integration	Potential Impact
Bite mark analysis	Precise modeling of bite marks	Automated pattern matching	Faster and more reliable identification
Age estimation	Detailed 3D dental structure scans	Age prediction through machine learning	Non-invasive and accurate
Dental identification in mass disasters	Creation of comprehensive 3D dental records	Automated search and matching	Speed up identification process

The application of 3D scanning technologies in forensic odontology is no doubt a quantum leap as far as gathering and processing evidence goes. As it is represented in the market projection graph Figure, from the year 2021 to 2030, significant growth is expected in the field of 3D scanning. These are driven by breakthroughs in technology, a reduction in cost, and the increased accuracy of 3D scans compared with the previous 2D scanning methods, thus enhancing the identification process of human remains. Most importantly, the integration of 3D scanning with artificial intelligence opens new horizons in forensic analysis. AI can help analyze complex 3D data sets and detect patterns that may be tricky for the human analyst to spot. Such a synergy of technologies is foreseen as further sealing the role of 3D scanning in forensic odontology with a view to further enhancing forensic practices and justice verdicts (Matsuda et al., 2020).A comparison of 2D and 3D scanning technologies in forensic odontology from 2010 to 2023 reflects a big difference in the adoption rate. Represented on this graph is the rate of adoption; though 2D imaging had dominated this area for quite some period of time, the spread of 3D scanning can be seen, showing upticks both in accuracy and detail It partially relates to the fact that 3D technology is more capable of fully and precisely modelling dental structures, which makes the identification process easier and increases the quality of forensic evidence. The application of artificial intelligence with 3D scanning is also a widening practice, and this is probably likely to accelerate its implementation even more. Besides, AI technologies have the potential to analyse advanced sets of data better, which helps raise the reliability of forensic investigations even higher. Yet another factor that is most probably going to continue, since forensic specialists understand more and more the reason for 3D against 2D approaches, is going to make the need for further training and investing in these innovative ways of imaging even more urgent (Ishwarkumar-Govender & Nalla, 2024).The graph of adoption versus time, as taken from the graph in Figure X, would serve to underpin that the trend of forensics odontology adoption has taken a dramatic turn for imaging technologies from 2010 through 2023. This drift toward the latest types of imaging methods-especially AI-enhanced 3D scanning-reveals an emerging awareness of their higher potential value in serving the purposes of forensic investigation. AI, when used with imaging technology, increases the accuracy of dental evidence examination and assists in finding patterns that are very difficult to be found using traditional methods. Graph: The emerging acceptance of AI-enhanced imaging is consistent with advances in technology and an increasing awareness of its benefits within the forensic community. This development is within the broader push toward digital solutions in forensic odontology and further underlines the fact that training and research remain crucial in perfecting these new breeds of tools (Li et al., 2024).

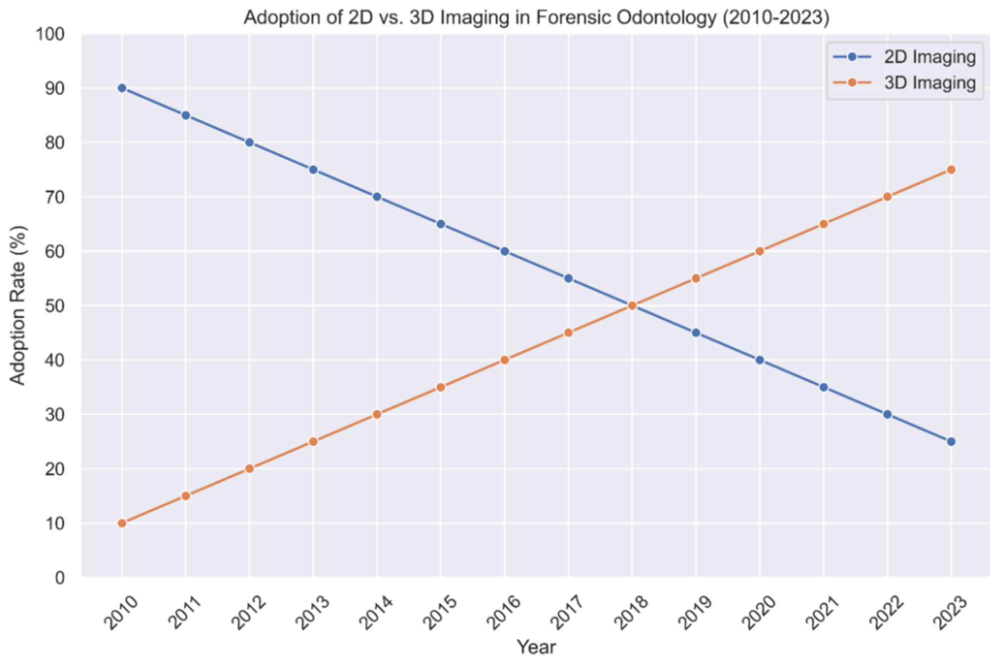
Adoption of imaging technologies, including AI-enhanced methods



3D Dental scanner market growth and projection (2021-2023)



Adoption of 2D vs 3D scanning in forensics odontology from 2010-2023



Conclusion

In this regard, the integration of 3D photo scan data and AI in forensic odontology enables the creation of extremely detailed models through the use of modern methods of photogrammetry and scanning for the capture of dental structure images that aid in identification. However, such techniques are likely to be burdened by errors related to lighting conditions, motion artifacts, and the precision of the scanners. The use of AI in this field has great potential, but it requires considerable expertise in software as well as in the interpretation of data. In the same way as other AI technologies, correct training and cautious application are extremely important to achieve accurate results. Where correct application of AI with 3D imagery is made, forensic investigations

Ricos Biology Journal ISSN 2959-3751 (Online), 2959-3743 (Print)
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become much quicker, more effective, and more reliable, and help considerably in the identification of human remains and in court processes. The technology has great promise, which, over the coming decades and with incorporation into more conventional processes, might just change the way the field works: eradicating human mistake and vastly improving results.

Declarations

Ethical approval and consent to participate: Not Applicable.

Consent for publication: Not applicable

Availability of data and materials: Not Applicable.

Competing interests : The authors have no conflicting interests.

Funding: None.

Authors' contributions: All the authors have made the same contribution to this review.

Acknowledgements

The authors would like to thank the University of Indonesia for providing support.

References

Abdel-Mottaleb, M., Nomir, O., Nassar, D. E., Fahmy, G., & Ammar, H. H. (2003). Challenges of developing an automated dental identification system. *2003 46th Midwest Symposium on Circuits and Systems*, *1*, 411–414.

Arunkumar, G., Athiraja, A., Arulraj, S., & Rajesh, P. (n.d.). COMPUTATION OF IMAGE DISTANCES FOR HUMAN IDENTIFICATION IN DENTAL RADIOGRAPHS. *International Journal of Electrical Engineering & Technology (IJEET)*, *10*(5). Retrieved 28 December 2023, from http://iaeme.com

Banday, M., & Mir, A. H. (2018). Forensic dental biometry-a human identification system using panoramic dental radiographs based on shape of mandibular bone. *International Journal of Biometrics*, *10*(4), 291–314. https://doi.org/10.1504/IJBM.2018.095284

Chalmers, E. V., McIntyre, G. T., Wang, W., Gillgrass, T., Martin, C. B., & Mossey, P. A. (2016). Intraoral 3D scanning or dental impressions for the assessment of dental arch relationships in cleft care: Which is superior? *Cleft Palate-Craniofacial Journal*, *53*(5), 568–577. https://doi.org/10.1597/15-036/ASSET/IMAGES/LARGE/10.1597_15-036-FIG7.JPEG

Chaudhary, R., Doggalli, N., Chandrakant, H., & Patil, K. (2018). Current and evolving applications of three-dimensional printing in forensic odontology: A review. *International Journal of Forensic Odontology*, *3*(2), 59. https://doi.org/10.4103/IJFO.IJFO_28_18

Chen, H., & Jain, A. K. (2005). Dental biometrics: Alignment and matching of dental radiographs. *IEEE Transactions on Pattern Analysis and Machine Intelligence*, *27*(8), 1319–1326. https://doi.org/10.1109/TPAMI.2005.157

Chomdej, T., Pankaow, W., & Choychumroon, S. (2006). Intelligent dental identification system (IDIS) in forensic medicine. *Forensic Science International*, *158*(1), 27–38.

Dong, X., Fan, F., Wu, W., Wen, H., Chen, H., Zhang, K., Zhang, J., & Deng, Z. (2022). Forensic Identification from Three-Dimensional Sphenoid Sinus Images Using the Iterative Closest Point Algorithm. *Journal of Digital Imaging*, *35*(4), 1034–1040. https://doi.org/10.1007/S10278-021-00572-W/FIGURES/6

Ebert, L. C., Thali, M. J., & Ross, S. (2011). Getting in touch—3D printing in Forensic Imaging. *Forensic Science International*, *211*(1–3), e1–e6. https://doi.org/10.1016/J.FORSCIINT.2011.04.022

Errickson, D., Thompson, T. J. U., & Rankin, B. W. J. (2014). The application of 3D visualization of osteological trauma for the courtroom: A critical review. *Journal of Forensic Radiology and Imaging*, *2*(3), 132–137. https://doi.org/10.1016/J.JOFRI.2014.04.002

Ishwarkumar-Govender, S., & Nalla, S. (2024). 3D technologies in dental arcade forensic research – A scoping review. *Translational Research in Anatomy*, *36*, 100313. https://doi.org/10.1016/J.TRIA.2024.100313

Jain, A. K., & Chen, H. (2004). Matching of dental X-ray images for human identification. *Pattern Recognition*, *37*(7), 1519–1532. https://doi.org/10.1016/J.PATCOG.2003.12.016

Johnson, A., Jani, G., Carew, R., & Pandey, A. (2021). Assessment of the accuracy of 3D printed teeth by various 3D printers in forensic odontology. *Forensic Science International*, *328*. https://doi.org/10.1016/J.FORSCIINT.2021.111044

Knivsberg, I. C., Kopperud, S. E., Bjørk, M. B., Torgersen, G., Skramstad, K., & Kvaal, S. I. (2022). Digitalised exercise material in forensic odontology. *International Journal of Legal Medicine*, *136*(1), 381–390. https://doi.org/10.1007/S00414-021-02740-7/TABLES/1

Kukade, M. J., Suhas Tivaskar, M., Luharia, M. A., Dhande, R., & Umate, R. (2022). Role Of Conventional Radiology In Gender Determination: A Review Article. *Journal of Pharmaceutical Negative Results*, *13*, 59–64. https://doi.org/10.47750/PNR.2022.13.S08.011

Kurniawan, A., Chusida, A., Utomo, H., Marini, M. I., Rizky, B. N., Prakoeswa, B. F. W., Hamdani, J., Salazar-Gamarra, R., Dib, L. L., Alias, A., Yusof, M. Y. P. M., & Marya, A. (2023). 3D Bitemark Analysis in Forensic Odontology Utilizing a Smartphone Camera and Open-Source Monoscopic Photogrammetry Surface Scanning. *Pesquisa Brasileira Em Odontopediatria e Clínica Integrada*, *23*, e220087. https://doi.org/10.1590/PBOCI.2023.001

Li, H., Xu, H., Li, Y., & Li, X. (2024). Application of artificial intelligence (AI)-enhanced biochemical sensing in molecular diagnosis and imaging analysis: Advancing and challenges. *TrAC Trends in Analytical Chemistry*, *174*, 117700. https://doi.org/10.1016/J.TRAC.2024.117700

Martin, C. B., Chalmers, E. V., McIntyre, G. T., Cochrane, H., & Mossey, P. A. (2015). Orthodontic scanners: what's available? *Journal of Orthodontics*, *42*(2), 136–143. https://doi.org/10.1179/1465313315Y.0000000001

Matsuda, S., Yoshida, H., Ebata, K., Shimada, I., & Yoshimura, H. (2020). Forensic odontology with digital technologies: A systematic review. *Journal of Forensic and Legal Medicine*, *74*, 102004. https://doi.org/10.1016/J.JFLM.2020.102004

Moraes, C. A. da C., Dias, P. E. M., & Melani, R. F. H. (2014). Demonstration of protocol for computer-aided forensic facial reconstruction with free software and photogrammetry. *Journal of Research in Dentistry*, *2*(1), 77. https://doi.org/10.19177/JRD.V2E1201477-90

Naidu, D., & Freer, T. J. (2013). Validity, reliability, and reproducibility of the iOC intraoral scanner: A comparison of tooth widths and Bolton ratios. *American Journal of Orthodontics and Dentofacial Orthopedics*, *144*(2), 304–310. https://doi.org/10.1016/J.AJODO.2013.04.011

Pitta, S. (2019). *Digital dentist: Providing specialized care through effortless technology: Exploring the feasibility of digitalisation in enhancing CRM in dentistry*. https://esource.dbs.ie/handle/10788/3814

Reesu, G. V., & Brown, N. L. (2022). Application of 3D imaging and selfies in forensic dental identification. *Journal of Forensic and Legal Medicine*, *89*. https://doi.org/10.1016/J.JFLM.2022.102354

Reesu, G. V., Woodsend, B., Mânica, S., Revie, G. F., Brown, N. L., & Mossey, P. A. (2020). Automated Identification from Dental Data (AutoIDD): A new development in digital forensics. *Forensic Science International*, *309*, 110218. https://doi.org/10.1016/J.FORSCIINT.2020.110218

Sieberth, T., Ebert, L. C., Gentile, S., & Fliss, B. (2020). Clinical forensic height measurements on injured people using a multi camera device for 3D documentation. *Forensic Science, Medicine and Pathology*, *16*, 586–594.

Simon, G., & Poór, V. S. (2022). Applications of 3D printing in forensic medicine and forensic pathology. A systematic review. *Annals of 3D Printed Medicine*, *8*, 100083. https://doi.org/10.1016/J.STLM.2022.100083

Singare, S., Shenggui, C., & Sheng, L. (2017). The use of 3D printing technology in human defect reconstruction-a review of cases study. *Medical Research and Innovations*, *1*(2). https://doi.org/10.15761/mri.1000109

Thurzo, A., Kosnáčová, H. S., Kurilová, V., Kosmeľ, S., Beňuš, R., Moravanský, N., Kováč, P., Kuracinová, K. M., Palkovič, M., & Varga, I. (2021). Use of Advanced Artificial Intelligence in Forensic Medicine, Forensic Anthropology and Clinical Anatomy. *Healthcare (Basel, Switzerland)*, *9*(11). https://doi.org/10.3390/HEALTHCARE9111545

Ting-shu, S., & Jian, S. (2015). Intraoral Digital Impression Technique: A Review. *Journal of Prosthodontics*, *24*(4), 313–321. https://doi.org/10.1111/JOPR.12218

Turkyilmaz, I., & Wilkins, G. N. (2021). 3D printing in dentistry – Exploring the new horizons. *Journal of Dental Sciences*, *16*(3), 1037. https://doi.org/10.1016/J.JDS.2021.04.004

Viner, M. D., & Robson, J. (2017). Post-Mortem Forensic Dental Radiography - a review of current techniques and future developments. *Journal of Forensic Radiology and Imaging*, *8*, 22–37. https://doi.org/10.1016/J.JOFRI.2017.03.007

Wang, J., Dou, J., Han, J., Li, G., & Tao, J. (2023). A population-based study to assess two convolutional neural networks for dental age estimation. *BMC Oral Health*, *23*(1), 1–9. https://doi.org/10.1186/S12903-023-02817-2/TABLES/

Wang, L., Mao, J., Hu, Y., & Sheng, W. (2020). Tooth identification based on teeth structure feature. *Systems Science & Control Engineering*, *8*(1), 521–533. https://doi.org/10.1080/21642583.2020.1825238

Wesemann, C., Muallah, J., Mah, J., & Bumann, A. (2017). Accuracy and efficiency of full-arch digitalization and 3D printing: A comparison between desktop model scanners, an intraoral scanner, a CBCT model scan, and stereolithographic 3D printing. *Quintessence International (Berlin, Germany : 1985)*, *48*(1), 41–50. https://doi.org/10.3290/J.QI.A37130

Yazdanian, M., Karami, S., Tahmasebi, E., Alam, M., Abbasi, K., Rahbar, M., Tebyaniyan, H., Ranjbar, R., Seifalian, A., & Yazdanian, A. (2022). Dental Radiographic/Digital Radiography Technology along with Biological Agents in Human Identification. *Scanning*, *2022*.