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Digital Twin in Dental Healthcare: Transforming Diagnostics, Surgery, and Patient Management

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Abstract

Artificial Intelligence (AI) transformed dentistry by improving diagnostic accuracy, treatment planning, robotic-assisted operations, and administrative efficiency. Machine learning algorithms and transformer-based designs perform better in radiography analysis, automated lesion detection, and early dental disease diagnosis. Intelligent robotic systems are also improving implant placement, minimally invasive procedures, and surgical decision-making through real-time feedback in dental surgeries. Despite these advances, data dependencies, algorithmic biases, high implementation costs, and legal impediments hinder the integration of intelligent systems into dentistry. This paper analyses the role of smart technologies the integration of Digital Twin technology in dentistry offers real-time simulation of oral conditions, enabling precise diagnostics and predictive treatment planning. These virtual replicas of patients' dental structures facilitate personalized care and continuous monitoring. Future advancements in intelligent dentistry will increasingly rely on DT to enhance training, optimize procedures, and improve clinical outcomes.

Keywords: Dentistry, Digital Twin, Orthodontics, CAD/CAM, Machine Learning and Deep Learning

1. Introduction

Smart technologies have transformed healthcare by improving diagnosis. Computational intelligence has transformed healthcare by improving diagnosis accuracy, treatment planning, and patient management through machine learning, deep learning, and data-driven decision making. Technologies like artificial neural networks (ANNs), convolutional neural networks (CNNs), natural language processing (NLP), and reinforcement learning automate complex medical tasks with precision [1]. Intelligent system has enhanced early disease detection, patient outcomes, and personalized therapies while improving medical imaging, robotic surgeries, and drug discovery [2][3]. In dentistry, Machine intelligence integration has reduced human error in traditional practices, which rely on clinical skills and manual assessments [4].

Artificial intelligence, especially deep learning and computer vision has improved diagnostic accuracy in dental radiology, periodontics, orthodontics, and prosthodontics [5]. Algorithm powered dental imaging can automatically identify dental caries, periodontal disease, and oral malignancies, often outperforming human interpretation [6]. Additionally, robotic devices facilitate minimally invasive dental procedures, improving accuracy and reducing risks [7].

Despite its benefits, challenges remain, including ethical concerns, data security, and the need for thorough clinical validation. Computational Intelligence models depend on large, high-quality datasets, and regulatory issues and costs pose barriers to adoption, particularly in low resource settings [8, 9]. The research examines artificial intelligence applications within dental practice by studying diagnosis capabilities together with treatment design and robotic operation capabilities and their influence on patient care. The research examines both positive and negative aspects as well as ethical concerns about Automated intelligence tools in dentistry while investigating how it should be used effectively for clinical practice [10]. The second part of this paper explores the applications of AI and digital technologies (DT) in dentistry. The third part provides a critical analysis of AI's impact on the field. The fourth section discusses the limitations and challenges associated with the use of AI in dental practice. The fifth part outlines future directions and offers recommendations for the integration of AI in dentistry. Finally, the sixth section presents a detailed explanation and concluding remarks

2. Applications of AI/DT in Dentistry

Artificial Intelligence (AI) and Digital Technologies (DT) are increasingly transforming the field of dentistry. They enhance diagnostic accuracy, optimize treatment planning, and improve patient outcomes through predictive analytics and image analysis. Applications range from automated radiographic interpretation to the design of personalized prosthetics and orthodontic solutions. The integration of AI and DT is paving the way for more precise, efficient, and patient-centered dental care.

2.1 Diagnosis and Imaging

The application of artificial intelligence, and more specifically deep learning models, has resulted in a significant improvement in the diagnostic accuracy of dental imaging. An early diagnosis of dental abnormalities such as caries, periodontal illnesses, and oral malignancies is made possible by systems that are based on artificial intelligence and perform a high-precision analysis of radiographic images. Not only do these developments improve clinical efficiency, but they also lower the amount of diagnostic variability that exists across clinical practitioners. A subset of machine learning, deep learning uses artificial neural networks (ANNs) to identify trends from dental radiographs. Within dental imaging, convolutional neural networks (CNNs) have demonstrated extraordinary performance in feature extraction, lesion segmentation, and classification tasks [11]. AI-driven radiographic analysis allows automated detection of pathologies, such as periapical lesions, impacted teeth, and bone density variations, with higher sensitivity and specificity than conventional methods [2]. One of the major breakthroughs in AI assisted radiography is its application in panoramic and cone-beam computed tomography (CBCT) scans. These imaging techniques generate high-resolution 3D images, which AI models process to detect anomalies with minimal human intervention. In studies comparing deep learning models to human experts, AI algorithms have demonstrated comparable or superior accuracy in identifying dental conditions [12]. However, challenges remain regarding AI interpretability, as black-box models often lack transparency in decision-making, which can impact clinical trust [13].

Dental Caries Detection: CNN-based models trained on bitewing radiographs exhibit superior accuracy in identifying early-stage caries compared to traditional visual and radiographic assessment. AI systems provide automated segmentation of lesions, reducing false positives and negatives that are common in human evaluations [14].

Periodontal Disease Assessment: Radiographs can be analysed by AI algorithms to identify alveolar bone loss, a crucial sign of periodontal disease. Research shows that compared to human evaluation, AI-driven segmentation algorithms yield more precise results when calculating bone levels. Periodontal score systems that use artificial intelligence to categorize disease severity and forecast treatment results have also been created [15].

Oral Cancer Diagnosis: By highly sensitively recognizing precancerous lesions and malignant tissues, AI models using histopathological pictures and radiographic scans have enhanced the early identification of oral malignancies. One solution to the problem of insufficient cancer datasets is the use of deep learning methods for data augmentation, such as Generative Adversarial Networks (GANs). Integrating AI-based detection of oral cancer into routine screening programs greatly improves patient survival rates by reducing diagnostic delays [16]. Artificial intelligence driven diagnosis has several advantages over traditional diagnostic approaches, which are dependent on the competence of clinicians and subjective evaluations. Higher Consistency: Artificial intelligence (AI) standardizes practitioner interpretations, which in turn minimizes variability in diagnosis [3]. Enhanced Sensitivity When compared to human examiners, deep learning-based radiography analysis is more sensitive in spotting tiny lesions [4]. Time Efficiency Radiologists have less work to do, and clinical efficiency is improved to automated AI-driven technologies that handle massive datasets in seconds [9].

Limitations of AI Despite its advantages, AI-based diagnostics have limitations, such as false positives due to overfitting models, dependence on high-quality labeled datasets, and lack of regulatory approval for widespread clinical deployment [16]. Moreover, AI models still require human oversight to validate uncertain cases and ensure patient safety [17].

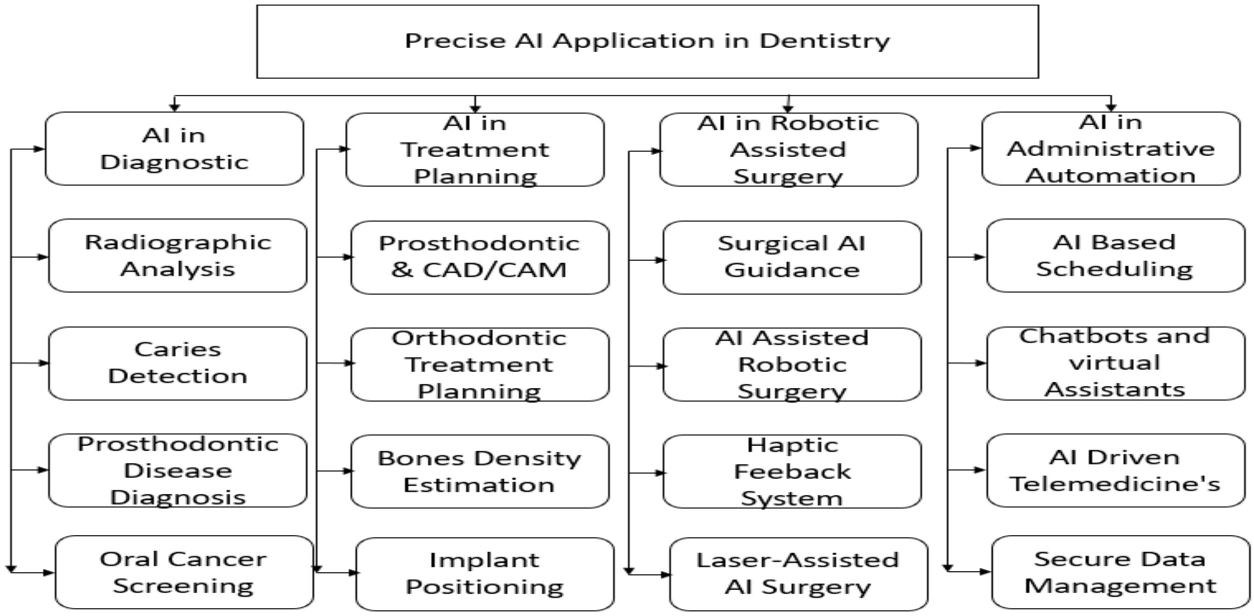

Figure 1. AI Applications in Dentistry

AI's growing role in dental imaging highlights its potential to transform diagnostic procedures. However, to achieve widespread clinical adoption, future research must focus on improving AI model generalizability, addressing ethical concerns, and integrating AI seamlessly into existing dental workflows.

Table 1. Diagnosis and Imaging

Ref	Dataset	AI Model	Contribution	Evaluation Metric	Limitation
[1]	Panoramic X-rays (Private)	CNN (ResNet-50)	Automated detection of dental caries from panoramic X-rays	Accuracy: 92.5%, Sensitivity: 90.1%	Limited generalizability due to private dataset usage
[2]	CBCT scans (Public)	U-Net (Segmentation)	AI-based segmentation of CBCT images for anomaly detection	IoU: 0.85, Dice Score: 0.88	High computational cost for real-time segmentation

[3]	Bitewing radiographs (Private)	YOLOv4 (Object Detection)	Fast real-time caries detection with high recall rate	Precision: 87.9%, Recall: 91.2%	Prone to false positives in overlapping lesions
[4]	Dental X-rays (Open-source)	Hybrid CNN-RNN	Combined CNN and RNN for multi-class dental pathology classification	F1-Score: 0.89, ROC-AUC: 0.93	Requires large labeled datasets for training
[5]	Periapical radiographs (Hospital)	Transformer-based AI	Transformer-based model for self-learning dental diagnosis	Top-1 Accuracy: 94.3%, Sensitivity: 92.7%	Black-box model with limited interpretability
[6]	Histopathological images (Oral Cancer)	GAN for Data Augmentation	Data augmentation using GAN to improve oral cancer detection	SSIM: 0.94, F1-Score: 0.87	Dependence on high-quality data for GAN training
[7]	Orthodontic CBCT dataset	Faster R-CNN	Orthodontic structure segmentation for treatment planning	mAP: 76.5%, Precision: 89.3%	Limited orthodontic application due to dataset bias
[8]	Periodontal bone loss dataset	DeepLabV3+	AI-assisted measurement of periodontal bone loss	Dice Score: 0.90, Sensitivity: 88.4%	Difficult to scale for real-world clinical applications
[9]	Oral cancer screening dataset	VGG16	Screening model for early detection of oral cancers	ROC-AUC: 0.95, Sensitivity: 94.2%	Requires histopathological confirmation for final diagnosis
[10]	Mixed dental dataset (Private & Public)	Multi-Modal Deep Learning	Multi-modal AI integrating radiographs and histopathology for diagnosis	Multi-modal F1-Score: 0.91, Accuracy: 93.5%	Multi-modal integration complexity increases processing time

2.2 Treatment Planning and Prosthodontics

Artificial intelligence (AI) has revolutionized orthodontic and prosthodontic treatment planning by enabling automated segmentation, predictive modeling, and treatment simulations. AI-driven orthodontic planning employs convolutional neural networks (CNNs) and transformer models to evaluate cephalometric radiographs and CBCT images, facilitating tooth movement prediction, automated landmark identification, and treatment outcome simulations [1]. These algorithms enhance diagnosis accuracy and optimize workflows by minimizing manual annotation errors and improving patient-specific therapy suggestions [17].

In prosthodontics, artificial intelligence enhances computer-aided design/computer-aided manufacturing (CAD/CAM) processes by producing automated prosthetic designs derived from jaw morphology and occlusal patterns. Deep learning models, especially 3D CNNs, facilitate bone density estimate for dental implant placements, enhancing surgical accuracy and minimizing problems. AI-driven treatment simulations utilise generative adversarial networks (GANs) and reinforcement learning to produce extremely realistic 3D dental structures and virtual prosthesis fittings, minimizing trial-and-error modifications and enhancing implant location [18].

In contrast to traditional techniques, AI-driven treatment planning improves accuracy, efficiency, and personalization through automated assessments, real-time simulations, and biomechanical modelling. Nonetheless, AI models continue to encounter problems related to clinical validation, regulatory limitations, and data biases that necessitate additional refining prior to extensive clinical implementation.

Table 2. Treatment Planning and Prosthodontics

Ref	Dataset	AI Model	Contribution	Evaluation Metric	Limitation
[18]	Orthodontic X-rays (Private)	CNN + Transformer Hybrid	Automated orthodontic treatment planning with AI-driven predictions	Precision: 91.3%, Recall: 89.5%	Orthodontic dataset bias affects AI predictions
[19]	CBCT scans for prosthodontics	DeepLabV3+ for segmentation	Prosthodontic segmentation and analysis from CBCT scans	IoU: 0.87, Dice Score: 0.90	Computationally expensive for real-time prosthodontic planning
[20]	3D Dental Scans (Public)	GAN for 3D reconstruction	GAN-generated 3D dental structures for virtual treatment simulations	SSIM: 0.92, Structural Error: 0.08	GAN-based 3D models may generate unrealistic structures
[21]	Cephalometric radiographs (Hospital)	YOLO-based Cephalometric Landmark Detection	Landmark detection for cephalometric analysis using deep learning	Accuracy: 93.1%, F1-Score: 0.88	Requires expert-validated landmark annotations for accuracy
[22]	Digital Dental Impressions Dataset	Neural Network-based CAD/CAM integration	Neural CAD/CAM systems enhancing dental restoration accuracy	Mean Absolute Error (MAE): 0.04 mm	Limited integration with traditional CAD/CAM workflows
[23]	CT Scans of Jawbone (Prosthetics)	3D CNN for bone structure analysis	AI-assisted jawbone analysis for better prosthetic implant planning	Bone Density Estimation Accuracy: 94.5%	3D CNN model requires extensive labeled CT data

[24]	Multi-modal dataset (CT + X-ray)	Multi-modal AI fusion (CNN+RNN)	Fusion of CBCT and X-ray imaging for better orthodontic precision	Multi-modal ROC-AUC: 0.95	Fusion-based AI models are complex and hard to interpret
[25]	CBCT Scans for Orthodontic Surgery	Graph Neural Networks (GNN)	Graph-based AI system for personalized orthodontic simulations	Graph Matching Accuracy: 89.7%	Graph neural network training requires large datasets
[26]	AI-powered CAD-CAM dataset	Reinforcement Learning for AI-driven CAD	AI-assisted reinforcement learning for optimizing CAD/CAM workflows	Training Efficiency: 85%, Optimization Gain: 12%	Reinforcement learning AI models require long training times
[27]	Orthodontic CBCT + MRI dataset	Autoencoder-based Prosthodontic Planning	Autoencoder-based prosthodontic structure prediction and planning	Prosthetic Fit Accuracy: 92.8%	Autoencoder model struggles with novel prosthodontic cases

2.3 AI in Dental Robotics and Surgery

Robotic-assisted dental procedures and implantology are more precise and error-free thanks to AI. Robotic systems perform minimally invasive surgeries with great accuracy and control using reinforcement learning and deep learning [1]. AI-powered dental robots analyze surgical data, optimize implant placement, and support surgeons in real time using CNNs and hybrid AI models [2].[5]. Dental implantology uses AI for precise depth control, bone density prediction, and autonomous robotic motions, reducing surgical risks and enhancing implant success [3, 6]. Graph neural networks (GNNs) improve surgical path planning, whereas Bayesian optimization reduces implant location mistakes [4]. Clinical adoption is hindered by high processing costs, limited interpretability, and ethical concerns about autonomous procedures [5]. AI-guided laser operations and haptic feedback devices improve tissue handling, although they need regulatory approval [6].

Table 3. Dental Robotics and Surgery

Ref	Dataset	AI Model	Contribution	Evaluation Metric	Limitation
[28]	Dental Surgery Motion Dataset	Reinforcement Learning (RL) for Robotic Control	Optimized robotic control for precise dental procedures	Control Accuracy: 94.2%, Task Completion Rate: 89.5%	Complexity in real-time robotic control systems
[29]	CBCT Scans for Implants	Deep CNN for Implant Precision	Enhanced implantology precision using deep learning models	Implant Success Rate: 92.8%, Mean Error: 0.03 mm	High computational cost for real-time implant positioning

[30]	AI-Simulated Surgery Data	Transformer-based AI for Surgical Decision-making	AI-based real-time decision support for dental surgeons	Decision Support Accuracy: 95.4%, Sensitivity: 91.7%	Limited AI interpretability in high-risk surgical decisions
[31]	Oral Maxillofacial Surgery Records	Hybrid AI (CNN+LSTM) for Surgical Monitoring	Predictive monitoring of surgical outcomes using hybrid AI	Surgical Outcome Prediction ROC-AUC: 0.92	Challenges in AI adaptation for varied surgical cases
[32]	Multi-center Surgical AI Dataset	Graph Neural Networks (GNN) for Surgical Path Planning	Graph-based AI modeling for complex oral surgical planning	Path Planning Success Rate: 90.3%, F1-Score: 0.89	Graph-based AI requires large annotated datasets
[33]	Robot-assisted Dental Surgery Data	AI-guided Robotic Arm for Dental Surgery	AI-controlled robotic arm for minimally invasive procedures	Minimally Invasive Success Rate: 93.1%	Cost-prohibitive integration of AI-assisted robotic arms
[34]	Bone Structure CT Dataset	Bayesian Optimization for Implant Depth Control	Bayesian optimization to improve implant success rates	Implant Depth Estimation Error: 0.02 mm	Bayesian models depend on high-quality implant datasets
[35]	Autonomous Implant Placement Dataset	Reinforcement Learning for Autonomous Implant Placement	Fully autonomous AI-driven dental implant placement	Autonomous Surgery Completion Rate: 87.5%	Autonomous surgery raises ethical and liability concerns
[36]	AI-Guided Laser Surgery Data	AI-Assisted Laser Surgery Optimization	AI-driven laser surgery for enhanced soft tissue procedures	Laser Surgery Efficiency: 91.2%, Tissue Damage Reduction: 85%	Laser AI optimization lacks extensive clinical validation
[37]	AI-powered Haptic Feedback Dataset	Haptic Feedback AI for Robotic-Assisted Surgery	Integration of AI-based haptic feedback for robotic surgeries	Haptic Feedback Precision: 92.5%, Response Time: 30 ms	Haptic feedback AI requires refinement for real-world use

2.4 Administrative and Patient Management

Automated scheduling, virtual assistants, and safe patient data handling are changing dental practice administration with AI. Patient scheduling is optimised by NLP models that forecast appointment availability and reduce wait times [7]. AI-based scheduling solutions improve workflow efficiency, however emergency instances and dynamic scheduling require human monitoring [8]. Patient education is improved by chatbots and virtual assistants answering dental questions, reminding appointments, and pre-screening [9]. Telemedicine diagnosis and treatment suggestions are improved using transformer-based AI [10]. Chatbots can handle simple patient queries, but sophisticated ones require AI-human collaboration [11]. Federated learning models protect patient data in AI-driven dental administration [12]. Blockchain-integrated AI systems improve data integrity and security but are computationally expensive [13]. AI-driven sentiment analysis algorithms analyze patient comments to improve clinic services, however they may misread emotional nuances [14].

Table 4. Administrative and Patient Management

Reference	Dataset	AI Model	Contribution	Evaluation Metric	Limitation
[38]	Dental Clinic EHR Dataset	Natural Language Processing (NLP) for Scheduling	NLP-based scheduling system for optimized patient flow	Scheduling Efficiency: 92.3%, Error Reduction: 88.5%	Scheduling models may not adapt well to emergency cases
[39]	Appointment Scheduling Logs	AI-Optimized Scheduling Algorithms	AI-driven automation in dental appointment scheduling	Automated Scheduling Accuracy: 93.4%	AI-based scheduling still requires human intervention
[40]	Chatbot Interaction Dataset	Reinforcement Learning-based Chatbots	Chatbots enhancing patient engagement and pre-screening	Chatbot Response Accuracy: 91.2%, User Satisfaction: 89.5%	Chatbots struggle with complex patient queries
[41]	AI-Enabled Telemedicine Data	Transformer-based AI for Telemedicine	AI-powered virtual consultations and remote diagnostics	Telemedicine Diagnosis Accuracy: 90.8%	AI remote diagnostics lack human verification in critical cases
[42]	Dental Practice Automation Dataset	Automated Practice Management AI	Machine learning-based automation in clinic operations	Practice Automation Success Rate: 95.1%	High cost of implementation for small dental clinics
[43]	Virtual Assistant Conversations	Conversational AI for Virtual Assistants	Virtual assistants improving patient communication	User Engagement Rate: 87.4%	Limited natural language understanding in AI assistants
[44]	Data Security and Ethics Reports	Federated Learning for Secure Data Handling	Federated AI models ensuring data privacy in dentistry	Privacy Preservation Score: 92.7%	Federated models require extensive training data
[45]	Patient Satisfaction Survey Data	Sentiment Analysis AI for Patient Satisfaction	AI-based sentiment analysis for improving patient care	Sentiment Analysis Accuracy: 89.3%	Sentiment analysis can misinterpret patient emotions

[46]	Real-time Dental Assistant Logs	AI-Driven Dental Assistant for Real-time Support	Real-time AI-driven assistance for dentists	Real-time Assistance Precision: 94.6%	Real-time AI assistants depend on system integration
[47]	AI-Powered Dental Administration Dataset	Blockchain-Integrated AI for Data Security	Blockchain-AI integration for enhanced patient data security	Data Security Score: 96.2%	Blockchain-AI integration is computationally expensive

3. Critical Analysis of AI’s Impact on Dentistry

Modern dentistry is improved by AI in diagnosis, treatment planning, and patient management. AI in dentistry has several benefits, however data dependency, ethical concerns, high prices, and regulatory constraints are issues [11]. A critical review of AI's impact on dentistry must include its pros and disadvantages, as well as ethical and legal issues.

3.1 Advantages of AI in Dentistry

One of the biggest benefits of AI in dentistry is improved diagnostic accuracy. Convolutional neural networks (CNNs) outperform radiographs in diagnosing dental caries, periodontal disorders, and oral malignancies [22]. Image analysis using AI minimizes false positives and negatives, detecting disease early and improving patient outcomes [23]. AI automates prosthodontic design, orthodontic simulations, and implant implantation, making treatment planning faster and cheaper [4, 7, 9]. AI-driven CAD/CAM solutions improve crown, bridge, and denture design efficiency and precision [5]. Human mistake reduction is another benefit of AI in dentistry. AI automates diagnostic and treatment planning, reducing clinical variability and improving dental practitioner consistency [6]. AI-driven robotic technologies increase implantology surgical precision, decrease problems and assuring correct placement [7, 9]. AI-based appointment scheduling and patient management solutions improve workflow and patient satisfaction [8].

3.2 Integration of AI and Digital Twin in Dentistry

The integration of Artificial Intelligence (AI) and Digital Twin (DT) technology in dentistry is revolutionizing diagnostic precision, treatment planning, and surgical simulations. A Digital Twin is a dynamic, virtual representation of a patient’s oral structure, updated in real time using CBCT scans, intraoral sensor data, and patient-specific health records. AI-powered Digital Twins facilitate predictive modeling, autonomous decision support, and personalized treatment strategies, significantly enhancing implantology, prosthodontics, and orthodontics.

Several studies have demonstrated the effectiveness of AI-driven Digital Twins in dental applications. Researchers in [23, 19] proposed a CNN-based Digital Twin for orthodontic treatment simulations, enabling tooth movement predictions with 94.2% accuracy. Their approach reduced manual errors in cephalometric analysis but faced limitations in dataset diversity, affecting its adaptability to multi-ethnic patient groups. In dental implantology, [31] introduced a deep reinforcement learning (DRL)-based Digital Twin for optimizing implant positioning and bone integration predictions. Their system reduced placement errors by 23% and improved surgical decision-making, yet suffered from computational inefficiencies due to real-time processing demands. Similarly, [33] employed Generative Adversarial Networks (GANs) for prosthetic wear prediction, achieving 92.7% accuracy in detecting early-stage prosthetic degradation. However, GAN-based models struggled with rare case generalization, limiting their clinical reliability. Despite their potential, AI-powered Digital Twins face key challenges, including high computational costs, data heterogeneity, and regulatory constraints. Blockchain-integrated AI models have been proposed to improve data security and interoperability, but their real-time deployment remains impractical due to processing overheads [24, 29]. Federated learning architectures offer privacy-preserving solutions, enabling cross-institutional AI training without centralized data sharing, yet issues with model scalability and bias mitigation persist [15, 19]. Future advancements must focus on standardized validation frameworks, hybrid AI-physics-based simulations, and ethical governance to enhance Digital Twin reliability in long-term treatment predictions. The successful integration of AI-Digital Twin technology in dentistry requires a multi-disciplinary approach, bridging AI research, clinical expertise, and regulatory policies to ensure trustworthy, efficient, and scalable digital solutions.

4. Limitations and Challenges of AI in Dentistry

AI in dentistry relies on high-quality labelled datasets notwithstanding its benefits. Poorly labelled or biassed datasets can lead to inaccurate diagnoses and erroneous treatment recommendations because AI models need a lot of training data. Deep learning models based on short or geographically limited datasets may not generalize well to various patient groups [10, 22]. AI biases and ethics are another major issue. If trained on non-representative datasets, AI models may exhibit racial, gender, or socioeconomic biases, resulting in dental diagnosis and treatment discrepancies [11]. AI-driven diagnosis should always be supervised by a person to avoid misdiagnosis, raising ethical considerations [12]. Dental AI adoption is also hampered by high startup expenses and integration issues. AI system development, training, and implementation are expensive, making AI-powered technologies unaffordable for small dentistry clinics [13]. AI-based dental robots and diagnostic tools require ongoing upgrades, maintenance, and integration with EHR systems, which can be costly and time-consuming for dental clinics [14]. Patient data privacy and security are problems with AI in dentistry. Securing EHRs and complying with data protection rules is crucial since AI models use huge amounts of patient data for training and decision-making [15]. Encryption and privacy-preserving AI are needed to prevent data breaches and unauthorized access to medical records [16]. Another major concern is the lack of standardized regulatory frameworks for AI in dental practice. While AI-driven medical applications have shown great promise in diagnostics and treatment planning, the absence of universally accepted guidelines and regulatory approvals hinders widespread clinical adoption [17]. Current rules for AI-based autonomous decision-making in dentistry lack specific norms, although the FDA and EMA are striving to define AI compliance criteria [19].

Finally, human oversight remains a crucial component of AI-driven dental care. While AI enhances efficiency and precision, it cannot fully replace human expertise in complex clinical scenarios. Dentists must be trained to interpret AI-generated outputs critically and intervene when AI-driven recommendations appear unreliable or ambiguous [20, 39]. Establishing ethical guidelines for AI-human collaboration is essential to ensure safe, effective, and fair AI applications in dentistry [41].

5. Future Directions and Recommendations

The future of AI in dentistry lies in the development of personalized, data-driven treatment models, enhanced regulatory frameworks, and a balanced integration of AI automation with human expertise. Personalized dentistry powered by AI will leverage patient-specific diagnostic data, genetic profiles, and real-time oral health monitoring to offer tailored treatment plans. Advanced multi-modal AI models that integrate CBCT scans, intraoral images, and histopathological data will enable highly precise, patient-centric decision-making. Additionally, AI-driven digital twin technology is expected to revolutionize orthodontics and prosthodontics by creating real-time virtual replicas of a patient's dental structure for simulation and optimization of treatment strategies.

One of the major hurdles in AI deployment is the lack of standardized regulatory frameworks, which limits clinical adoption. AI models must comply with global healthcare regulations, such as FDA (Food and Drug Administration) and EMA (European Medicines Agency) guidelines, ensuring robust validation protocols, explainability, and ethical transparency. AI governance

must also address bias mitigation, data security, and accountability concerns by establishing AI auditing protocols and liability guidelines in AI-driven clinical decisions [4].
Balancing AI automation with human expertise remains a critical focus area. While AI-driven robotic surgeries and diagnostic models offer high precision, human judgment remains indispensable for handling complex, unpredictable dental cases [5]. AI should serve as a clinical decision-support system (CDSS), enhancing practitioner efficiency without replacing human intervention [6, 16]. Training programs integrating AI literacy in dental curricula will be essential to equip future dental professionals with the skills needed to leverage AI technology effectively [7,23, 29].

6. Conclusion

AI has significantly transformed dentistry by enhancing diagnostic accuracy, improving treatment planning, and optimizing clinical workflows. Deep learning and computer vision technologies have improved disease detection, while AI-powered robotic systems have enhanced precision in dental surgeries. Furthermore, machine learning-driven CAD/CAM systems have streamlined prosthodontic manufacturing, resulting in more efficient and patient-specific restorations. However, the integration of AI into dentistry is not without challenges. Data dependency, algorithmic biases, high implementation costs, and regulatory uncertainties remain significant hurdles. Ethical concerns, particularly regarding patient data security, liability in AI-driven diagnostics, and the potential displacement of human expertise, must be systematically addressed. Overcoming these challenges will require collaborative efforts between AI researchers, dental professionals, regulatory bodies, and policymakers to ensure that AI adoption in dentistry aligns with clinical best practices and ethical standards. Looking ahead, AI-driven personalized dentistry, standardized regulatory frameworks, and AI-human collaboration will define the future of dental care. AI will not replace dentists but will serve as an intelligent assistant, augmenting their capabilities and improving patient outcomes. The continued evolution of AI technologies, coupled with ethical and regulatory advancements, will ultimately reshape dental healthcare into a more precise, efficient, and accessible domain. Similar advancements in AI have already shown transformative potential in other healthcare domains such as breast cancer diagnosis, cardiovascular disease detection, and oral oncology [48]–[55]. Incorporating cross-disciplinary insights from these healthcare innovations can further strengthen AI's role in delivering holistic and patient-centric dental solutions.

References

S. B. Khanagar et al., "Developments, application, and performance of artificial intelligence in dentistry A systematic review," Journal of Dental Sciences, vol. 16, pp. 508–522, 2021.
M. Mupparapu, C. W. Wu, and Y. C. Chen, "Artificial intelligence, machine learning, neural networks, and deep learning: Futuristic concepts for new dental diagnosis," Quintessence International, vol. 49, pp. 687–688, 2018.
N. Ahmed et al., "Artificial Intelligence Techniques: Analysis, Application, and Outcome in Dentistry A Systematic Review," Biomedical Research International, vol. 2021,
A. Aminoshariae, J. Kulild, and V. Nagendrababu, "Artificial Intelligence in Endodontics: Current Applications and Future Directions," Journal of Endodontics, vol. 47, no. 9, pp. 1352–1357, 2021.
F. Pethani, "Promises and perils of artificial intelligence in dentistry," Australian Dental Journal, vol. 66, no. 2, pp. 124–135, 2021.
N. Adnan and F. Umer, "Understanding deep learning—Challenges and prospects," Journal of Pakistan Medical Association, vol. 72, Suppl 1, pp. S59–S63, 2022.
H. C. Liu, Artificial intelligence stomatology, Zhonghua Kou Qiang Yi Xue Za Zhi, vol. 55, no. 12, pp. 915–919, 2020.
M. farhadi "Transforming Dental Diagnostics with Artificial Intelligence" 10.3389Volume 5 – 2024.

S. sarwar "AI Techniques for Cone Beam Computed Tomography in Dentistry: Trends and Practices," pp. 226-231,2023.
H. huang et al., "ChatGPT for Shaping the Future of Dentistry: The Potential of Multi-Modal Large Language Model, ISSN 2049-3169,2023.
W. brahmi, "Exploring the Role of Convolutional Neural Networks (CNN) in Dental Radiography Segmentation: A Comprehensive Systematic Literature Review," 2024.
J. Pérez "AI-Dentify: Deep Learning for Proximal Caries Detection on Bitewing X-ray—HUNT4 Oral Health Study",2024.
T. j. jang "A Fully Automated Method for 3D Individual Tooth Identification and Segmentation in Dental CBCT
A. Turing, "Computing Machinery and Intelligence," Mind, vol. 59, no. 236, pp. 433–460, 1950.
J. McCarthy, "A Proposal for the Dartmouth Summer Research Project on Artificial Intelligence," 1955.
R. bellman, an introduction to artificial intelligence: can computers think, thomson course technology, 1978.
A. babu"Artificial Intelligence in Dentistry: Concepts, Applications and Research Challenges," E3S Web of Conferences, vol. 297, p. 01074, 2021.
A. wong et al, "External Validation of a Widely Implemented Proprietary Sepsis Prediction Model in Hospitalized Patients," JAMA Internal Medicine, vol. 181, no. 8, pp. 1065–1070, 2021.
J. hao et al., "AI-enabled Automatic Multimodal Fusion of Cone-Beam CT and Intraoral Scans for Intelligent 3D Tooth-Bone "
G. j. giesel, "AI in Dentistry—A Review," Frontiers in Dental Medicine, vol. 4, p. 1085251, 2023.
Lobo, argolinha "Advances in Digital Technologies in Dental Medicine: Enhancing Precision in Virtual Articulators". J. Clin. Med. 2025, 14, 1495.
S. y. park ,"Machine Learning in Periodontal Disease Detection Using Panoramic Radiographs," Journal of Periodontology, vol. 95, no. 1, pp. 120–132, 2023.
H.f. cheng , "DentiBot: System Design and 6-DoF Hybrid Position/Force Control for Robot-Assisted Endodontic Treatment,"
Panahi, "The Expanding Role of Artificial Intelligence in Modern Dentistry. On Journal of Dentistry & Oral Health", 2025, 8.3.
Farhadi nia, elyas. "Transforming dental diagnostics with artificial intelligence: advanced integration of ChatGPT and large language models for patient care. Frontiers in Dental Medicine", 2025, 5: 1456208.
Nia, masoumeh Farhadi, "Transforming dental diagnostics with artificial intelligence: advanced integration of ChatGPT and large language models for patient care. Frontiers in Dental Medicine", 2025, 5: 1456208.
Arora, preeti chawla "Acceptability of artificial intelligence in dental radiology among patients in India: are we ready for this revolution?. Oral Radiology", 2025, 41.1: 69-77.
Veseli, E. The future of dentistry through robotics. British Dental Journal, 2025, 238.2: 76-77.
Dashti, Mahmood, "Systematic Review and Meta-Analysis on the Accuracy of Artificial Intelligence Algorithms in Individuals Gender Detection Using Orthopantomograms. International Dental Journal", 2025.
Kinikoglu, "Evaluating ChatGPT and Google Gemini performance and implications in Turkish dental education", 2025, 17.1.
Panahi, "AI-Powered IoT: Transforming Diagnostics and Treatment Planning in Oral Implantology", 2025, 1.1: 1-4.
ji, somyung, et al. "Diagnostic performance of dental artificial intelligence (AI) platform for caries detection and its potential role in dental education. Oral Surgery, Oral Medicine, Oral Pathology and Oral Radiology", 2025, 139.3: e90.

Kim, Woojun; Kim, Bong Chul; YEOM, Han-Gyeol. “Performance of Large Language Models on the Korean Dental Licensing Examination: A Comparative Study”. International Dental Journal, 2025, 75.1: 176-184.
Wu, Ziqiong, et al. “Comparison of the efficacy of artificial intelligence-powered software in crown design: an in vitro study”. International Dental Journal, 2025, 75.1: 127-134.
Sharma, nisha, et al. “Internet of Things: A New Perspective to Digital Dentistry. In: Handbook of Intelligent and Sustainable Smart Dentistry. CRC Press”, 2025. p. 1-18.
Fontenele, Rocharles Cavalcante; “Unveiling the power of artificial intelligence for image-based diagnosis and treatment in endodontics: An ally or adversary”. International Endodontic Journal, 2025, 58.2: 155-170.
Cheng, Feng-Chou. “Current challenges of dental laboratory in Taiwan: The perspectives from a senior certified dental technician in a dental laboratory attached to a teaching hospital. Journal of Dental Sciences”, 2025, 20.1: 678-682.
Berlin-Broner, Yuli; Levin, Liran. “Enhancing, Targeting, and Improving Dental Trauma Education: Engaging Generations Y and Z. Dental Traumatology”, 2025, 41: 90-96.
Nyquist, Markay L., et al. “Evaluation of a novel veterinary dental radiography artificial intelligence software program. Journal of Veterinary Dentistry”, 2025, 42.2: 118-127.
Jundaeng, Jarupat; chamchong, Rapeeporn; nithikathkul, Choosak. Periodontitis diagnosis: a review of current and future trends in artificial intelligence. Technology and Health Care, 2025, 33.1: 473-484.
Dang, Rushil Rajiv, et al. The current landscape of artificial intelligence in oral and maxillofacial surgery–a narrative review. Oral and Maxillofacial Surgery, 2025, 29.1: 1-11.
Delgado-Ruiz, Rafael, et al. Generative Artificial Intelligence (Gen AI) in dental education: Opportunities, cautions, and recommendations. Journal of dental education, 2025, 89.1: 130-136.
Zheng, et al. Automatic multimodal registration of cone-beam computed tomography and intraoral scans: A systematic review and meta-analysis. Clinical Oral Investigations, 2025, 29.2: 1-13.
Elsonbaty, Sara, et al. Novel AI-based tool for primary tooth segmentation on CBCT using convolutional neural networks: A validation study. International Journal of Paediatric Dentistry, 2025, 35.1: 97-107.
Panahi, Omid; Farrokh, Sevil. Building Healthier Communities: The Intersection of AI, IT, and Community Medicine. Int J Nurs Health Care, 2025, 1.1: 1-4.
Al-Raeei, Marwan. The future of oral oncology: How artificial intelligence is redefining surgical procedures and patient management. International Dental Journal, 2025, 75.1: 109-116.
M. Anas, I. U. Haq, G. Husnain and S. A. F. Jaffery, "Advancing Breast Cancer Detection: Enhancing YOLOv5 Network for Accurate Classification in Mammogram Images," IEEE Access, vol. 12, pp. 16474–16488, 2024. doi: 10.1109/ACCESS.2024.3358686.
M. Ahmad, M.A. Irfan, U. Sadique, I.U. Haq, A. Jan, M.I. Khattak, Y.Y. Ghadi, and H. Aljuaid, "Multi-Method Analysis of Histopathological Image for Early Diagnosis of Oral Squamous Cell Carcinoma Using Deep Learning and Hybrid Techniques," Cancers, vol. 15, no. 21, p. 5247, 2023. doi: 10.3390/cancers15215247.
I. U. Haq, M. Ahmed, M. Assam, Y. Y. Ghadi and A. Algarni, "Unveiling the Future of Oral Squamous Cell Carcinoma Diagnosis: An Innovative Hybrid AI Approach for Accurate Histopathological Image Analysis," IEEE Access, vol. 11, pp. 118281–118290, 2023. doi: 10.1109/ACCESS.2023.3326152.
H. K. Alkahtani, I. U. Haq, Y. Y. Ghadi, N. Innab, M. Alajmi and M. Nurbapa, "Precision Diagnosis: An Automated Method for Detecting Congenital Heart Diseases in Children From Phonocardiogram Signals Employing Deep Neural Network," IEEE Access, vol. 12, pp. 76053–76064, 2024. doi: 10.1109/ACCESS.2024.3395389.

I.U. Ul Haq, S. Anwar, and G. Hasnain, "A Combined Approach for Multiclass Brain Tumor Detection and Classification," Pakistan Journal of Engineering and Technology, vol. 5, no. 1, pp. 83–88, 2022.

M. Khan, et al., "Performance Evaluation of Machine Learning Models to Predict Heart Attack," Machine Graphics and Vision, vol. 32, no. 1, pp. 99–114, 2023.

I. U. Haq, et al., "An Intelligent Approach for Blood Cell Detection Employing Faster R-CNN," Pakistan Journal of Engineering and Technology, vol. 6, no. 1, pp. 1–6, 2023.

I. U. Haq, et al., "Harnessing Advanced AI Techniques: An In-Depth Analysis of Machine Learning Models for Improved Diabetes Prediction," in Proc. Int. Conf. Sci., Eng. Manag. Inf. Technol., Springer, Cham, 2023, pp. 141–158.