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The Digital Transformation of Dentistry: AI-Driven Innovations and Clinical Challenges

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Abstract Artificial intelligence (AI) and digital technologies are increasingly reshaping contemporary dental practice, influencing diagnostic accuracy, treatment planning, and clinical workflows across multiple dental specialties. This review synthesizes current evidence on the clinical applications of AI and digital dentistry, with particular emphasis on diagnostic imaging, intraoral scanning, CAD/CAM systems, three-dimensional (3D) printing, and integrated digital workflows in prosthodontics, orthodontics, implantology, and surgical dentistry. AI-assisted diagnostic systems demonstrate promising performance in radiographic interpretation, occlusal analysis, and early lesion detection, supporting clinical decision-making and reducing diagnostic variability. Digital technologies, including intraoral scanning and additive manufacturing, enhance treatment precision, chairside efficiency, patient comfort, and communication while facilitating streamlined documentation and interdisciplinary collaboration. However, challenges related to high initial investment costs, clinician training, data privacy, cybersecurity, and the need for robust clinical validation of AI algorithms continue to limit widespread adoption. Evidence from current literature indicates that while these technologies offer substantial benefits as adjuncts to clinical expertise, their successful integration into routine dental practice requires evidence-based implementation, standardized clinical protocols, and continued validation through high-quality clinical and outcome-based research.

Keywords: *Artificial intelligence, Digital dentistry, Intraoral scanning, CAD/CAM, 3D printing, Dental diagnostics, Clinical workflows, Prosthodontics, Orthodontics, Implant dentistry*

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1. Introduction

The integration of digital technologies has progressively reshaped contemporary dental practice, influencing diagnostic accuracy, treatment planning, and clinical execution across multiple specialties. Early adoption of computer-aided design and computer-aided manufacturing (CAD/CAM) systems marked a shift from conventional analog workflows toward digitally driven dentistry, enabling improved precision and reproducibility in restorative and prosthetic procedures. This digital transformation has since expanded to include intraoral scanners, cone-beam computed tomography (CBCT), virtual articulators, and three-dimensional (3D) printing, collectively establishing the foundation of modern digital dentistry. [1]

Recent advancements in artificial intelligence (AI), particularly machine learning and deep learning algorithms, have further enhanced the capabilities of digital dental systems. AI-based tools are increasingly applied to radiographic interpretation, caries detection, periodontal assessment, and analysis of craniofacial structures, demonstrating promising diagnostic performance comparable to experienced clinicians in controlled settings. These developments highlight AI's potential to support clinical decision-making and reduce diagnostic variability. [2]

Beyond diagnostics, digital technologies play a critical role in treatment planning and execution. Virtual planning software combined with intraoral scanning and CBCT imaging has improved predictability in prosthodontics, orthodontics, and implantology by enabling prosthetically

driven and patient-specific treatment approaches. In implant dentistry, digital workflows incorporating guided surgery and 3D-printed surgical templates have been shown to enhance placement accuracy and reduce surgical complications. In orthodontics, AI-assisted treatment simulation and automated tooth movement analysis facilitate customized appliance design and monitoring, while in prosthodontics, CAD/CAM and additive manufacturing technologies allow for efficient fabrication of restorations with consistent quality. Collectively, these innovations contribute to reduced chair time, improved patient communication, and enhanced clinical outcomes. [3]

The objective of this review is to critically evaluate the clinical applications of artificial intelligence and digital technologies in dentistry, with emphasis on diagnosis, treatment planning, prosthodontics, orthodontics, and surgical disciplines. Additionally, this paper aims to discuss the current challenges and limitations associated with clinical implementation, as well as the future opportunities for integrating AI-driven digital workflows into routine dental practice.

2. Artificial Intelligence in Clinical Dentistry

2.1. Diagnostic Applications

2.1.1. AI for Radiographic Analysis

Artificial intelligence has demonstrated significant potential in the interpretation of dental radiographs, particularly in the detection of caries, periapical pathologies, and periodontal bone loss. Deep learning models trained on large datasets of bitewing, periapical, and panoramic radiographs have shown high sensitivity and specificity for caries detection, often matching or exceeding the diagnostic performance of experienced clinicians under controlled conditions. [4]

Similarly, AI-based systems have been developed for automated detection of periapical lesions on periapical radiographs and CBCT scans, reducing diagnostic variability and facilitating early intervention. In periodontology, convolutional neural networks have been applied to quantify alveolar bone loss and classify periodontal disease severity on radiographs, offering objective and reproducible assessments that may support clinical decision-making and longitudinal monitoring. [4]

2.1.2. Occlusal Analysis and Bite Assessment

AI algorithms have also been introduced for occlusal analysis and bite assessment, utilizing digital impressions, virtual articulators, and pressure-mapping data. These systems enable quantitative evaluation of occlusal contacts and force distribution, which is particularly relevant in prosthodontics and full-mouth rehabilitation cases. Preliminary studies suggest that AI-assisted occlusal analysis may improve occlusal accuracy and reduce adjustment time compared with conventional articulating paper methods. [5]

2.1.3. Early Detection of Oral Lesions and Pathologies

Early detection of oral potentially malignant disorders and oral cancer remains a critical clinical challenge. AI-based image analysis systems using intraoral photographs and histopathological images have shown promising results in identifying suspicious lesions at early stages. Systematic reviews report high diagnostic accuracy of deep learning models for oral cancer screening, highlighting their potential role as adjunctive tools in routine clinical examinations [6]

2.2. AI-Assisted Treatment Planning

2.2.1. Prosthodontic Planning

In prosthodontics, AI-driven software integrated with CAD/CAM systems assists in the design of crowns, bridges, and complete dentures. Automated margin detection, tooth morphology prediction, and occlusal optimization contribute to improved restoration accuracy and reduced laboratory turnaround time. Clinical evaluations suggest that AI-assisted digital workflows enhance consistency and predictability in prosthetic outcomes. [7]

2.2.2. Orthodontic Treatment Simulation

Orthodontics has rapidly adopted AI for treatment simulation and virtual setup planning. Machine learning algorithms can analyze craniofacial morphology, predict tooth movement, and generate optimized treatment plans for clear aligner therapy. These technologies support individualized treatment strategies and facilitate patient communication through visual simulation of anticipated outcomes. [8]

2.2.3. Implant Placement and Guided Surgery

AI-assisted implant planning combines CBCT data with intraoral scans to enable prosthetically driven implant placement. Automated anatomical landmark identification and bone quality assessment improve planning accuracy, while integration with 3D-printed surgical guides enhances precision during clinical execution. Evidence suggests that digitally planned, AI-supported guided surgery results in reduced positional deviation and improved safety compared with freehand implant placement. [9]

2.3. Predictive Analytics in Dentistry

Predictive analytics represents a growing application of AI in clinical dentistry, focusing on disease risk assessment and outcome prediction. AI models trained on patient-specific data, including radiographs, clinical indices, and behavioral factors, have been used to forecast caries risk and periodontal disease progression with promising accuracy. Furthermore, predictive algorithms can assist clinicians in estimating treatment outcomes and complications, supporting evidence-based decision-making and personalized care planning. By integrating patient-specific variables, AI systems may facilitate tailored treatment recommendations that align with precision dentistry principles. [10] Figure 1

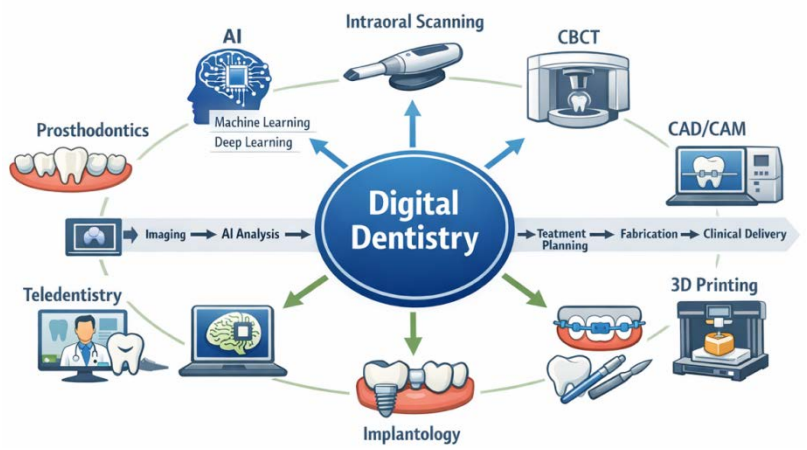

Figure 1. Digital dentistry in different principles

3. Digital Technologies in Clinical Practice

3.1. Intraoral Scanning

3.1.1. Accuracy Compared with Conventional Impressions

Intraoral scanning has become a cornerstone of digital dentistry, offering an alternative to conventional elastomeric impressions. Numerous clinical and in vitro studies have evaluated the accuracy of intraoral scanners in terms of trueness and precision. Systematic reviews indicate that for single units and short-span fixed dental prostheses, intraoral scanners demonstrate accuracy comparable to, and in some cases exceeding, conventional impression techniques. [11]

For full-arch impressions, accuracy remains technique- and system-dependent; however, continuous advancements in scanning technology and software algorithms have significantly improved outcomes, making intraoral scanning clinically acceptable for an expanding range of indications. [11]

3.1.2. Impact on Prosthodontic, Orthodontic, and Implant Workflows

In prosthodontics, intraoral scanning facilitates seamless integration with CAD/CAM systems, enabling efficient fabrication of crowns, bridges, and implant-supported restorations with reduced laboratory turnaround time. Digital impressions also allow for improved communication between clinicians and dental technicians, contributing to enhanced restoration accuracy. [12]

In orthodontics, digital models derived from intraoral scans are routinely used for diagnosis, treatment planning, and aligner fabrication. Studies demonstrate that digital models are clinically equivalent to plaster casts for orthodontic measurements, while offering superior storage, retrieval, and data-sharing capabilities. [13]

In implant dentistry, intraoral scanning combined with CBCT data enables precise prosthetically driven planning and guided surgery. Digital impressions eliminate errors associated with impression material distortion and allow accurate transfer of implant positions to the virtual environment. [14]

3.1.3. Patient Comfort and Chairside Efficiency

From a patient-centered perspective, intraoral scanning is associated with improved comfort compared with conventional impressions, particularly for patients with gag reflex or anxiety. Clinical studies consistently report reduced chairside time and higher patient preference for digital impressions, supporting their routine clinical adoption. This advantage is especially pronounced in pediatric populations, where tolerance and cooperation are critical to clinical success. Evidence from randomized crossover clinical investigations involving children aged 7-11 years has demonstrated that intraoral scanning is significantly better tolerated than conventional polyvinyl siloxane impressions. Digital impressions were preferred by the majority of pediatric patients and were associated with significantly shorter procedure times, higher comfort scores, and a reduced gag reflex as assessed using visual analogue scales. These findings reinforce the role of intraoral scanning as a patient-friendly alternative to conventional impression techniques and highlight its clinical value in pediatric and anxiety-prone patient groups. [15]

3.2.3. D Printing and CAD/CAM Technologies

3.2.1. Prosthodontic Applications

CAD/CAM and additive manufacturing technologies have transformed prosthodontic rehabilitation by enabling precise and reproducible fabrication of restorations. Milled ceramic and resin-based crowns and bridges demonstrate favorable marginal adaptation and mechanical properties comparable to conventionally fabricated restorations. Three-dimensional printing has gained increasing acceptance for the fabrication of complete and partial dentures, particularly in digital denture workflows, offering reduced production time and standardized outcomes. [16]

3.2.2. Surgical Guides for Implantology

In implant dentistry, 3D-printed surgical guides generated through digital planning workflows improve the accuracy and predictability of implant placement. Systematic reviews demonstrate that guided implant surgery reduces angular and linear deviations compared

with freehand techniques, thereby enhancing surgical safety, particularly in anatomically complex cases. [17]

3.2.3. Orthodontic Aligners and Splints

Additive manufacturing plays a critical role in orthodontics, particularly in the production of clear aligners, retainers, and occlusal splints. Digital workflows allow for precise control of tooth movement, staging and appliance customization, resulting in predictable orthodontic outcomes. Current evidence supports the clinical reliability of digitally fabricated aligners and splints when proper planning protocols are followed. [18]

3.3. Integration into Daily Clinical Practice

3.3.1. Digital Workflow from Diagnosis to Treatment Delivery

The integration of intraoral scanning, CBCT imaging, CAD/CAM design, and 3D printing has enabled comprehensive digital workflows that span diagnosis, treatment planning, and clinical execution. These workflows enhance interdisciplinary collaboration and allow real-time visualization of treatment outcomes, improving both clinical efficiency and patient communication. [19] Figure 2

3.3.2. Teledentistry and Remote Consultation

Teledentistry represents an extension of digital dentistry, enabling remote consultation, triage, and follow-up care. Recent studies highlight its effectiveness in improving access to dental services, particularly in underserved populations, while maintaining diagnostic reliability for selected clinical conditions. The integration of digital imaging, electronic health records, and AI-assisted diagnostics is expected to further expand the scope of teledentistry, supporting continuity of care and patient-centered clinical models. [20]

4. Clinical Benefits and Challenges in Clinical Implementation

The clinical adoption of artificial intelligence and digital technologies in dentistry offers substantial benefits while also presenting notable challenges. Table 1

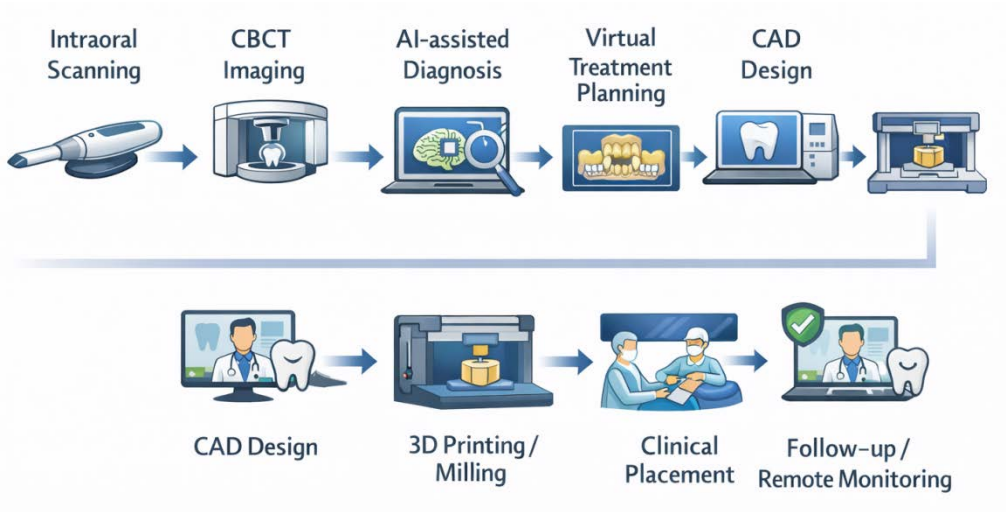

Figure 2. Digital workflow

Table 1. Clinical Benefits and Challenges of Artificial Intelligence and Digital Technologies in Dentistry

Domain	Clinical Benefits	Challenges in Clinical Implementation
Treatment Precision and Predictability	Digital workflows and AI-assisted planning enhance the accuracy and predictability of restorative, orthodontic, and implant treatments through improved visualization, standardized protocols, and data-driven decision-making. [21,22]	Variability in software performance and lack of universal standards may affect consistency across platforms and limit reproducibility in different clinical settings. [22]
Chairside Efficiency and Error Reduction	Reduced chair time, fewer remakes, and minimized manual errors are achieved through automation of diagnostic, design, and fabrication processes, leading to more efficient clinical workflows. [23]	Initial setup, calibration issues, and system integration problems may offset time savings during early adoption phases. [23-26]
Patient Communication and Engagement	Visual treatment planning tools, digital simulations, and virtual mock-ups improve patient understanding, acceptance, and satisfaction by clearly demonstrating proposed treatment outcomes. [26,27]	Overreliance on visual simulations may create unrealistic patient expectations if clinical limitations are not adequately communicated. [26,27]
Documentation and Record-Keeping	Digital records enable accurate storage, easy retrieval, and efficient sharing of clinical data, supporting interdisciplinary collaboration and long-term patient monitoring. [28]	Data privacy, cybersecurity risks, and compliance with health information regulations present significant concerns requiring robust safeguards.[28]
Economic and Operational Factors	Long-term cost-effectiveness may be achieved through improved efficiency, reduced material waste, and optimized workflows. [29]	High initial investment costs for hardware, software licenses, and maintenance remain a major barrier, particularly for small or solo practices.[29]

Domain	Clinical Benefits	Challenges in Clinical Implementation
Clinical Skill Development	Digital tools can support clinical decision-making and standardize treatment quality across varying experience levels. [30]	A steep learning curve and need for continuous training may limit adoption, especially among clinicians unfamiliar with advanced digital systems. [30]
Reliability and Clinical Validation	Emerging evidence supports the clinical usefulness of AI-driven tools as adjuncts to clinician judgment. [30]	Limited external validation, potential algorithm bias, and insufficient long-term clinical outcome data raise concerns regarding reliability and generalizability. [30]

5. Future Perspectives in Clinical Dentistry

5.1. Personalized and Patient-Centered Care through AI Guidance

The continued integration of artificial intelligence into digital dental workflows is expected to advance the shift toward personalized, patient-centered care. By analyzing large volumes of patient-specific data, including clinical findings, radiographic images, medical history, and behavioural factors, AI systems may support clinicians in tailoring diagnostic and therapeutic strategies to individual risk profiles and treatment needs. Such precision-oriented approaches have the potential to improve treatment outcomes, enhance preventive care strategies, and optimize long-term oral health management. [31]

5.2. Smart Materials and AI-Driven Workflows

Emerging developments in dental materials science, particularly the introduction of smart and bioactive materials, are anticipated to further enhance digital dentistry when combined with AI-driven workflows. AI-assisted design and manufacturing processes may optimize material selection, restoration geometry, and occlusal morphology based on functional and biomechanical requirements. The convergence of smart materials with digital design and fabrication technologies is likely to contribute to restorations with improved longevity, adaptability, and clinical performance. [32]

5.3. Remote Monitoring and Virtual Care Integration

Remote monitoring and virtual care represent important future directions for digital dentistry, particularly in the context of follow-up care, orthodontic treatment supervision, and chronic disease management. AI-assisted analysis of digital images and patient-reported data may enable early detection of complications and reduce the need for in-person visits. The integration of teledentistry platforms with digital records and AI-based diagnostic support could enhance access to care, promote continuity of treatment, and support patient engagement beyond the clinical setting. [33]

5.4. Future Research Directions

Despite promising advancements, further research is required to support the widespread clinical adoption of AI and digital technologies. Future studies should prioritize well-designed clinical trials, long-term outcome-based research, and external validation of AI algorithms across diverse patient populations and clinical environments. Standardized reporting methodologies and comparative effectiveness studies will be essential to establish robust evidence for safety, reliability, and clinical benefit. [34]

6. Conclusion

Artificial intelligence and digital technologies are increasingly influencing contemporary dental practice by enhancing diagnostic accuracy, treatment planning, and clinical efficiency across multiple dental disciplines. Digital workflows incorporating intraoral scanning, CAD/CAM, 3D printing, and AI-based decision support offer significant benefits, including improved treatment precision, reduced chairside time, and enhanced patient communication.

However, challenges related to cost, training requirements, data security, and the clinical validation of AI systems remain barriers to widespread implementation. Evidence-based adoption, supported by standardized protocols and rigorous clinical research, is essential to ensure that these technologies function as effective adjuncts rather than replacements for clinical expertise. In conclusion, while AI and digital technologies hold considerable promise for advancing dental care, their successful integration into routine practice will depend on continued clinical validation, interdisciplinary collaboration, and a commitment to patient-centered, evidence-based dentistry.

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