

Recent Advances in Digital Dentistry: The Impact of Robotics and Smart Implant Design on Dental Practice



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Abstract:

Introduction: Digital dentistry has transformed modern practice through CAD/CAM, intraoral scanners, and AI technologies, while robotic surgery and smart implants further enhance precision and clinical outcomes. The aim of this article is to evaluate the evolution and impact of digital dental technologies, with particular emphasis on robotic-assisted implantology and smart implant design.

Methods: This study presents a narrative review of peer-reviewed articles, clinical trials, and systematic reviews published in the past five years, identified through MEDLINE, PubMed, Scopus, and Google Scholar.

Results: Robotic-assisted implant placement improves accuracy by up to 98.2%, reduces surgical errors, and shortens operative time. Smart implants promote osseointegration and lower the risk of peri-implantitis through bioelectric stimulation. In addition, digital workflows enhance diagnostic precision and shorten treatment turnaround times.

Discussion: Robotic-assisted implantology and smart implant design are reshaping precision and longevity in modern dental practice. Robotic systems enhance surgical accuracy, reduce procedural errors, and support patient-specific planning, particularly in complex implant cases. At the same time, bioelectric smart implants actively promote tissue regeneration and help mitigate peri-implantitis, marking a shift from passive to responsive implantology. Together, these technologies point toward a transformative future for digital dentistry, although challenges related to cost, training, and regulatory validation remain critical for broader implementation.

Conclusion: Advancements in digital dentistry, particularly robotics and smart implants, are transforming clinical practice by improving precision and patient outcomes. Broader integration, however, will require overcoming current limitations related to cost, accessibility, and regulatory frameworks, supported by ongoing research and professional development.

Keywords: Digital dentistry, CAD/CAM, Intraoral scanners, Dental implants, Robotics, Smart implant design, Peri-implant health, Osseointegration.

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1. INTRODUCTION

The field of dentistry has witnessed remarkable advancements with the integration of digital technologies, significantly improving diagnostic accuracy, treatment planning, and patient outcomes [1, 2]. Digital dentistry encompasses a wide range of innovations, including CAD/CAM systems, digital X-rays, 3D imaging, intraoral scanners, and digital smile design, all aimed at enhancing the efficiency, precision, and comfort of dental treatments [3]. These technologies not only optimize workflows but also enable more predictable, minimally invasive procedures, improving the overall treatment experience and satisfaction. Moreover, they contribute to the professional development of dental practitioners by enhancing their skills and expertise in utilizing cutting-edge tools [4, 5].

Additionally, digital dentistry has also supported the adoption of telemedicine and visualization technologies such as augmented and virtual reality (AR/VR), which enhances remote consultations, patient education, and virtual surgical planning. In addition, rapid prototyping through 3D printing has optimized prosthetic fabrication and treatment workflows. While relevant to the broader field of digital dentistry, these technologies serve primarily as contextual background and are not the central focus of this review [6].

One of the most transformative applications of digital technology is in the field of dental implantology, where recent advancements in robotics and Smart Implant Design (SID) are revolutionizing implant procedures. Dental implants have long been regarded as the gold standard for tooth replacement, offering superior functionality, aesthetics, and long-term stability compared to conventional prostheses. Unlike traditional bridges and dentures, implants integrate with the jawbone through osseointegration, providing a permanent and reliable solution for edentulism. This is supported by histological findings from a clinical study by Traini *et al.* (2011), which evaluated an immediately loaded implant retrieved after 23 months. The study reported a high bone-to-implant contact (BIC) rate of 76.7% and significant peri-implant bone remodeling, indicating that, despite successful osseointegration, factors such as collagen fiber orientation and osteocyte density can influence long-term stability and implant fatigue risk [7]. However, despite their high success rates, challenges such as implant failure, peri-implantitis, and biomechanical complications remain prevalent. Addressing these challenges, innovative digital solutions have emerged to

enhance precision, reduce surgical invasiveness, and improve implant longevity [5, 8, 9].

Two groundbreaking developments, robotic-assisted implant placement and smart implants, are at the forefront of modern implantology. Robotic-assisted surgery is gaining prominence for its ability to enhance surgical accuracy, optimize implant positioning, and minimize complications related to human error [10, 11]. By incorporating Artificial Intelligence (AI) and real-time feedback mechanisms, robotics improves treatment planning and execution, leading to better clinical outcomes, reduced surgical time, and fewer postoperative complications. This level of precision is particularly crucial in complex implant cases where millimeter-level accuracy can significantly impact success rates [11, 12].

Another major advancement is the development of smart implants, which extend beyond traditional osseointegration by incorporating bioelectric stimulation [12]. These implants generate electric signals upon biting, promoting gingival tissue healing, enhancing blood circulation, and reducing bacterial accumulation around the implant site. Such bioelectric functionality presents a promising solution to peri-implantitis, one of the leading causes of implant failure, and contributes to long-term implant stability. Additionally, smart implants hold the potential to integrate with digital monitoring systems, providing real-time data on osseointegration progress and implant health, further optimizing patient care [13, 14].

As digital dentistry continues to evolve, it is crucial to study these emerging technologies to fully understand their clinical applications, benefits, and limitations. This review explores the latest advancements in robotic-assisted implant placement and smart implant design, assessing their impact on treatment precision, patient experience, and long-term success. Additionally, it examines the broader role of digital dentistry in optimizing diagnostic and treatment processes, contributing to the continuous evolution of oral healthcare. Understanding these innovations is essential for clinicians seeking to adopt advanced solutions that enhance patient outcomes and improve the overall standard of care in modern dental practice.

1.1. Objectives

This study aims to:

1- Evaluate the impact of digital dentistry by examining the role of technologies such as CAD/CAM, 3D imaging, intraoral scanners, digital smile design, and

robotic-assisted implant placement in enhancing diagnostic accuracy, treatment planning, surgical precision, and overall clinical outcomes.

2- Identify Key Benefits and Challenges: Highlight the advantages of these technologies in reducing surgical invasiveness, improving patient comfort, and increasing implant longevity while addressing barriers such as high costs, learning curves, and implementation challenges.

3- Propose Future Directions: Discuss potential developments in digital dentistry and implantology, including AI integration, real-time monitoring of implants, and cost-effective solutions for widespread clinical adoption.

2. METHODOLOGY

To achieve the above objectives, a narrative literature review was conducted following a semi-structured approach:

2.1. Data Sources and Search Strategy

Relevant studies were identified using databases such as MEDLINE, PubMed, Google Scholar, and Scopus.

The search was conducted using keywords including: "digital dentistry," "CAD/CAM," "robotic-assisted implant placement," "smart dental implants," "peri-implant health," and "AI in dentistry."

Only peer-reviewed articles, clinical trials, and systematic reviews published in the last five years were included to ensure up-to-date findings. A total of 10 studies were included in the final review.

2.2. Selection Criteria

2.2.1. Inclusion

Studies discussing digital dentistry advancements, robotics in implant placement, and smart implant technologies with clinical relevance.

2.2.2. Exclusion

Non-peer-reviewed articles, outdated studies, and research with inconclusive or anecdotal evidence.

2.3. Data Extraction and Analysis

Information on digital workflows, robotic accuracy, smart implant functionality, treatment efficiency, and patient outcomes was extracted. Comparative analysis of robotic-assisted implant placement *versus* conventional methods was conducted. Potential limitations and challenges were assessed, with emphasis on implementation barriers and cost factors.

2.4. Synthesis and Interpretation

Findings were categorized based on technological impact, clinical effectiveness, patient benefits, and limitations. Emerging trends and future research directions were identified. Practical recommendations for integrating these technologies into clinical practice were proposed.

This methodology ensures a structured, evidence-based approach to understanding how digital dentistry,

robotics, and smart implant technology are transforming modern dental practice and implantology.

3. RESULTS

3.1. Advancements in Digital Dentistry and Implantology

The integration of digital technologies in dentistry has significantly improved diagnostic accuracy, treatment planning, and clinical workflows. Innovations such as Artificial Intelligence (AI), Computer-Aided Design (CAD), digital imaging, and big data analysis have simplified the procedures, enhancing efficiency and treatment outcomes. AI-powered diagnostic tools improve decision-making by analyzing vast datasets, leading to more precise and personalized treatment plans. Machine learning and computational biological analysis further refine treatment predictions, optimizing long-term patient care.

3.2. Robotic-assisted Implant Placement

Robotic-assisted technology has transformed dental implantology by enhancing surgical precision and optimizing implant positioning. Systems such as Yomi (NEOCIS Inc.) integrate real-time navigation and automated adjustments based on preoperative digital planning, reducing surgical time and minimizing human error. Studies indicate that robotic-assisted procedures lead to greater implant stability, reduced marginal bone loss, and improved long-term success rates. The ability to achieve sub-millimeter accuracy has made robotics particularly beneficial in complex implant cases, where precise angulation and depth are crucial for osseointegration. Furthermore, robotics is associated with improved placement accuracy and may reduce intraoperative deviations and operative time; however, evidence for faster healing remains preliminary and has not been consistently demonstrated in robust clinical trials.

A recent systematic review by Ravipati *et al.* (2024) [15] analyzed 13 *in vitro* studies and reported mean entry deviations of 0.72 ± 0.68 mm, exit deviations of 0.86 ± 0.92 mm, and angular deviations of $1.47 \pm 1.61^\circ$. These findings indicate that robotic-assisted procedures may achieve superior accuracy compared to conventional computer-assisted methods. However, it is important to note that these results are derived from *in vitro* models and have not yet been consistently validated in large-scale clinical trials. Therefore, while robotics shows strong potential for improving implant placement accuracy, further clinical investigations are essential before definitive conclusions can be drawn regarding their real-world effectiveness.

3.3. Smart Dental Implants and Bioelectronic Innovations

A major breakthrough in implantology is the development of smart dental implants that integrate bioelectronic features to improve peri-implant health. These implants are designed to generate electrical impulses during mastication, potentially stimulating gingival blood flow, promoting tissue healing, and exerting antibacterial effects. Early investigations, such as the pilot work by Park *et al.* (2020) [16], introduced the concept of a Human Oral

Motion-Powered Smart Dental Implant (SDI) capable of delivering ambulatory photo-biomodulation therapy. Preclinical studies have also suggested that bioelectrical stimulation may accelerate osseointegration and reduce the risk of peri-implantitis.

However, it is important to emphasize that most of the current evidence remains preclinical or limited to small-scale pilot studies, with outcomes largely confined to experimental models. While these early findings highlight a promising direction for future innovation, well-powered clinical trials are still lacking, and long-term safety and efficacy have not been fully established. Therefore, smart implant bioelectric stimulation should presently be regarded as an emerging experimental concept rather than a validated clinical strategy.

Smart implants have been experimentally designed to incorporate piezoelectric ceramics, which can convert mechanical forces into electrical energy, with the potential to support tissue regeneration and exert antibacterial effects. These properties may help enhance implant stability and reduce complications associated with microbial colonization, although current evidence remains largely preclinical. In addition, emerging smart materials are being explored for their ability to enable real-time monitoring of implant health, such as detecting early signs of bone-implant integration or complications, but such applications are still at the experimental stage and require validation through robust clinical studies [16].

4. DISCUSSION

4.1. The Role of Robotics and Smart Implants in Dental Implantology

The integration of robotics in dental implantology has significantly enhanced surgical precision, efficiency, and patient outcomes [17, 18]. Robotic-assisted systems provide real-time navigation, allowing for accurate implant placement while reducing reliance on manual techniques. These systems support minimally invasive procedures and can reduce guidance errors during placement. While some previous studies [19-24] suggest comparable or reduced early postoperative complications, definitive evidence for accelerated healing is limited; accordingly, we emphasize the need for multicenter randomized trials to confirm any recovery advantages.

Despite these advantages, the implementation of robotic technology in dental implantology presents challenges [25, 26], including high costs, the need for specialized training, and limited accessibility in clinical settings. Many dental professionals require extensive training to fully utilize robotic systems, delaying widespread implementation. Additionally, the financial burden of acquiring and maintaining robotic-assisted technology restricts its use to high-end dental centers, limiting accessibility for a broader patient population [27].

On the other hand, smart dental implants represent a paradigm shift by introducing bioelectrical stimulation for active peri-implant maintenance. Unlike traditional implants, which passively integrate into the bone, smart implants generate mild electric currents when subjected to

occlusal forces. This enhances blood circulation, promotes gingival tissue regeneration, and exerts antimicrobial effects, reducing bacterial colonization. By actively inhibiting bacterial growth and fostering a healthier peri-implant environment, smart implants have the potential to improve long-term implant stability and reduce the incidence of peri-implantitis—a leading cause of implant failure [17, 28-32].

4.2. Durability and Mechanical Reliability of Embedded Electronics

Smart or bioelectronic implants must maintain mechanical and electrical stability in a humid, chemically complex, and dynamically loaded environment. Piezoelectric ceramics and associated electrodes/interconnects can be vulnerable to fatigue-related microcracking, depolarization, hydrothermal aging, corrosion, and delamination, especially at coating-substrate interfaces. The addition of energy-harvesting modules and sensors increases the importance of robust hermetic sealing and long-term insulation to prevent moisture ingress and electrical drift during mastication-scale loading. Recent materials-science work on hybrid/smart coatings and piezoelectric implant surfaces highlights both promise and failure modes that must be mitigated before routine clinical use [28-33]. Consistent with these findings, we emphasize that durability claims for smart implants should be validated through ISO-aligned fatigue/corrosion testing and prospective clinical studies evaluating electronic reliability alongside peri-implant outcomes.

Future advancements in robotic and smart implant technology will likely focus on refining robotic systems for broader clinical applications and on enhancing smart implant materials to improve performance [34]. The integration of Artificial Intelligence (AI) [35, 36] into robotic-assisted implant placement may further enhance treatment planning by enabling real-time decision-making through predictive analytics. Additionally, advances in bioresponsive materials could enable implants to dynamically adapt to changing oral conditions, promoting better osseointegration and long-term stability [37].

4.3. Digital Dentistry: Advancements and Applications

Digital dentistry began in the late 20th century with the introduction of digital X-rays, dental imaging, 3D CT scans, and Computer-Aided Design (CAD) and planning. Digital X-rays provide high-quality images quickly and with reduced radiation exposure, improving case diagnosis and treatment planning. The use of CAD enhances the design and manufacture of dental implants, improving precision and lowering errors [38-44]. Table 1 shows comparison of traditional vs. digital dentistry.

4.4. Key Concepts in Digital Dentistry [40-44]

4.4.1. Information and Communications Technology (ICT)

Enhances medical information management and improves diagnosis and treatment procedures.

Table 1. Comparison of traditional vs. digital dentistry.

Factor	Traditional Dentistry	Digital Dentistry
Precision in Diagnosis	Employs traditional radiographs with variable diagnostic accuracy.	Employs digital X-rays with AI for improved diagnosis.
Treatment Efficiency	Time-consuming, with multiple visits.	Rapid diagnosis and treatment via CAD/CAM and 3D printing.
Patient Comfort	Invasive and uncomfortable procedures.	Minimally invasive for better patient comfort.
Sustainability	Higher material use raises environmental impact.	Full digital workflows minimize waste.
Cost*	Lower upfront investment (average implant placement cost ≈ USD 1,500-2,000 per case), but long-term inefficiencies due to manual errors, remakes, and extended chair time increase overall expenditure.	Higher upfront investment (CAD/CAM ≈ USD 100k-150k; robotics ≈ USD 150k-300k), but long-term savings arise from up to 40% fewer prosthetic remakes and 20-30 minutes less chairside time per case."

Note: * "Cost estimates are approximate and drawn from published data on CAD/CAM adoption, robotic-assisted dental implant systems, and clinical efficiency studies. Actual costs vary by region, practice scale, and equipment model." [45-48]."

4.4.2. Digital Dental Imaging

Facilitates highly accurate case diagnosis and efficient treatment planning.

4.4.3. Computer-Aided Design (CAD)

Enables precise design and manufacturing of dental restorations, reducing errors and improving treatment quality.

4.4.4. Artificial Intelligence (AI)

Enhances therapeutic decision-making by analyzing vast amounts of medical data, improving diagnostic accuracy and treatment efficacy.

4.4.5. Big Data Analysis

Examines large amounts of medical data to identify significant patterns and trends that contribute to improved patient care.

4.4.6. Digital Smile Design

Uses 3D imaging and AI-driven software to create personalized treatment plans, allowing patients to visualize their potential outcomes before undergoing procedures.

4.5. Applications of Digital Dentistry

4.5.1. Advanced Diagnostic Tools

Digital imaging provides high-resolution, detailed images for precise diagnoses, disease progression tracking, and effective treatment planning.

4.5.2. Computer-Aided Manufacturing (CAM)

CAD/CAM-generated dental restorations enhance efficiency, quality, and repeatability in dental treatment.

4.5.3. 3D Printing in Dentistry

3D dental printing technology is used for producing dental implants, crowns, and orthodontic appliances with high precision and reduced production costs.

4.5.4. Virtual and Augmented Reality

These technologies facilitate advanced treatment simulations, enhance patient education, and improve dental training experiences.

4.5.5. Robotic-Assisted Dental Procedures

Robotics are increasingly used in minimally invasive surgeries and implant placements, improving accuracy and patient outcomes.

4.5.6. Wireless Interoperability (IoT)

The interconnectivity of digital dental equipment improves data management, communication, and overall efficiency in clinical settings.

5. LIMITATIONS

This review is subject to several limitations. First, only ten studies met the inclusion criteria, which inevitably narrows the evidence base and may limit the generalizability of the conclusions. This limited number reflects both the field's novelty and the stringent eligibility criteria applied, as only peer-reviewed studies, clinical trials, and systematic reviews published in the last five years were considered. While this ensured that the findings were based on recent and clinically relevant data, it also excluded potentially valuable older studies and those published in languages other than English. Additionally, the limited pool of studies may not capture the full diversity of clinical outcomes, patient populations, or long-term follow-up data related to robotic-assisted implantology and smart implant technologies. Publication bias and the predominance of *in vitro* and early clinical studies further constrain the comprehensiveness of the evidence. Future systematic reviews should consider a broader timeframe and include ongoing and upcoming clinical trials to provide a more robust assessment of these emerging technologies.

CONCLUSION

The integration of robotics and digital technologies into dental practice presents a meaningful evolution in implantology, aligning with the core goal of improving treatment precision, safety, and patient satisfaction. This review highlights how robotic-assisted systems and smart implant designs can contribute to more predictable surgical outcomes and enhanced peri-implant health when appropriately implemented. However, these technologies are still in the early stages of widespread clinical use and must be approached with measured expectations. Their successful integration depends not only on their technical potential but also on addressing systemic barriers such as practitioner training, high operational costs, and regulatory

approval pathways. As digital dentistry evolves, interdisciplinary collaboration and robust clinical validation will be essential to ensuring that these innovations translate into sustainable and equitable improvements in patient care. Ultimately, the findings support cautious optimism about the role of robotics and smart implants in shaping the future of implant therapy, provided that their limitations are acknowledged and strategically addressed.

IMPACT AND FUTURE CONSIDERATIONS

Future trends in digital dentistry are rapidly evolving, and several of our predictions already have real-world implementations in ongoing clinical research or commercial systems. For AI-assisted robotics, image-guided robotic implant platforms have received multiple FDA 510(k) clearances and are being evaluated in comparative clinical studies. [49, 50] For real-time monitoring, smart-implant prototypes with embedded sensing/energy-harvesting have been demonstrated in preclinical engineering studies, while non-invasive stability monitoring is already routine in clinics. However, embedded “smart” electronics for continuous surveillance remain at an early stage and require prospective human trials before routine adoption.

AI-ASSISTED / IMAGE-GUIDED ROBOTICS (CLINICAL & COMMERCIAL)

A robotic navigational system for dental implants has FDA 510(k) clearance, including indications for partially and fully edentulous patients and guided bone reduction, evidencing mature commercialization. Recent randomized controlled and observational clinical studies compare robot-assisted *versus* freehand placement with respect to accuracy and efficiency.

REAL-TIME MONITORING (PROTOTYPE → CLINIC)

Smart-implant prototypes that convert oral motion to power photo-biomodulation and on-implant electronics have been reported in preclinical work; complementary proof-of-concept studies demonstrate implant stability monitoring using piezoelectric/vibration signatures and machine learning. Non-invasive stability tools (*e.g.*, RFA/ISQ) are already used clinically, but fully embedded, telemetric systems remain experimental and have not yet been tested in large human trials. [16]

AUTHORS' CONTRIBUTIONS

The authors confirm their contributions to the paper as follows: W.Z.A., H.A., and D.F.: Research concept and study design, wrote the original draft, and edited the final paper; Y.R.E., M.A.S., M.A., D.S., A.K., and S.S.: Data gathering, analysis, and interpretation of results. All authors reviewed the results and approved the final version of the manuscript.

LIST OF ABBREVIATIONS

CAD/CAM = Computer-Aided Design/Computer-Aided Manufacturing.

SID = Smart Implant Design.

IoT = Internet of Things

CONSENT FOR PUBLICATION

Not applicable.

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CONFLICT OF INTEREST

The authors declare no conflict of interest, financial or otherwise.

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