REVIEW ARTICLE

The Application of Artificial Intelligence and Nanotechnology in Implant Dentistry, Periodontology, Orthodontics, and Surgical Procedures: A Review

Faeze Mohammad Hassani[1], Mina Abasi[2], Shirin Kolahdouz[3], Amir Masoud Zarasvandi[4], Moslem Taghizadeh[5], Mohammad Davoudi[6], Mina Alibemani[7*]

[1] Department of Pharmacology and Toxicology, School of Pharmacy, Shahid Beheshti University of Medical Sciences, Tehran, Iran.

[2] School of Dentistry, Tehran University of Medical Sciences, Tehran, Iran.

[3] Research Unit of Population Health, Faculty of Medicine and Dentistry, University of Oulu, Finland.

[4] Dental Student of Istanbul Okan University, Istanbul, Turkey

[5] General Practitioner of Dentistry, Faculty of Dentistry, Cheboksary University of Medical Sciences, Russia.

[6] Department of Oral and Maxillofacial Pathology, Mashhad Dental School, Mashhad University of Medical Sciences, Mashhad, Iran.

[7] Department of Endodontics, Mashhad Dental School, Mashhad University of Medical Sciences, Mashhad, Iran.

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ABSTRACT

The integration of artificial intelligence (AI) and nanotechnology in dentistry marks a transformative advancement across implant dentistry, periodontology, orthodontics, and oral surgery. AI technologies, including machine learning and deep learning, enhance diagnostic accuracy, treatment planning, and predictive modeling, enabling personalized and efficient patient care. Concurrently, nanotechnology improves dental biomaterials and implant surface properties, promoting osseointegration, antimicrobial effects, and tissue regeneration. This review comprehensively explores recent innovations and clinical applications of AI and nanotechnology, addressing their synergistic roles in improving outcomes, reducing complications, and advancing therapeutic approaches. Despite promising benefits, challenges related to ethical considerations, data privacy, cost, accessibility, and regulatory compliance remain. Future research directions emphasize the need for robust validation, cost-effectiveness, and interdisciplinary collaboration to optimize the safe and equitable adoption of these technologies. The ongoing convergence of AI and nanotechnology holds great potential to revolutionize dental care, balancing technological innovation with clinical expertise for improved patient outcomes.

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INTRODUCTION

The integration of artificial intelligence (AI) and nanotechnology in dentistry represents a significant leap forward, offering innovative solutions for diagnosis, treatment, and patient care. AI, through machine learning and data analysis, has transformed oral health diagnosis and treatment planning, enhancing precision and efficiency across dental disciplines, including implantology where it assists in implant identification, planning, and predicting outcomes, often surpassing traditional methods[1,2]. Simultaneously, nanotechnology has revolutionized dental materials and procedures by improving strength, durability, and biocompatibility of implants and restoratives, providing antibacterial properties and enhancing osseointegration[3-5]. Nanomaterials enable precise pain management, tooth restoration, orthodontic therapy, and early disease detection

* Corresponding Author Email: *minabemani@gmail.com*

with targeted drug delivery, optimizing therapeutic effects and minimizing side effects[6, 7]. Recent advancements include AI models for patient risk classification and managing peri-implantitis, as well as nanoparticles that enhance material strength, aesthetics, and implant stability[1, 2, 8]. This review aims to comprehensively explore AI and nanotechnology applications in implant dentistry, periodontology, orthodontics, and surgery, highlighting their clinical applications, innovations, benefits, challenges, and future research directions, including safety, cost-effectiveness, and regulatory issues to ensure their sustained impact on dental care and patient outcomes.

FUNDAMENTALS OF ARTIFICIAL INTELLIGENCE AND NANOTECHNOLOGY IN DENTISTRY

The integration of AI and nanotechnology in dentistry marks a significant advancement, offering innovative solutions for diagnosis, treatment, and prevention. AI technologies such as machine learning, deep learning, and robotics are transforming dental practices by enhancing precision and efficiency: machine learning and deep learning analyze large datasets for early disease detection, diagnostic tools, treatment planning, and personalized medicine, while robotics improve surgical precision and control in procedures like root canal therapy and maxillofacial surgery[9, 10]. Concurrently, nanotechnology leverages nanomaterials with high surface area-to-volume ratios and tunable properties to enhance mechanical, antimicrobial, and biocompatible characteristics of dental restoratives and implants, promoting osseointegration and tissue regeneration[7, 11, 12]. Emerging concepts like nanorobots hold potential for precise, minimally invasive interventions in tooth repair, drug delivery, and orthodontics[13, 14]. Nanoscale technologies enable development of advanced restorative materials and targeted drug delivery systems that support bone and periodontal regeneration[11, 15]. Despite these promising advancements, challenges remain, including concerns about nanomaterial cytotoxicity and long-term biocompatibility, ethical issues in AI, high costs, and regulatory hurdles, which must be addressed through future research to ensure the safe and effective clinical adoption of these technologies.

AI AND NANOTECHNOLOGY IN IMPLANT DENTISTRY

The integration of AI and nanotechnology in implant dentistry is transforming the field by improving precision, efficiency, and patient outcomes. AI is extensively employed in implant planning, surgical guidance[2, 16], prosthetic design[17], and predictive modeling[2, 18]; it aids in evaluating bone dimensions, identifying critical anatomical landmarks, optimizing implant designs to minimize stress, and predicting the success of implants by analyzing patient risk factors and radiographic data. Additionally, deep learning algorithms enhance diagnostic accuracy through high-precision image analysis[16, 17]. Complementing these advancements, nanotechnology improves implant surface properties by promoting osseointegration through nanoscale modifications that mimic natural bone formation[4, 19], reducing infection risks with antimicrobial nanoparticle coatings[19, 20], and allowing tailored surface chemistry to enhance tissue integration and reduce rejection rates[20, 21].

APPLICATIONS IN PERIODONTOLOGY

The integration of AI and nanotechnology in periodontology is transforming the field by enhancing diagnostic accuracy, treatment planning, and therapeutic outcomes. AI technologies, including machine learning, deep learning, and convolutional neural networks, improve early detection and risk prediction of periodontal diseases by analyzing patient data, biomarkers, and clinical signs more accurately and rapidly than traditional methods[22-24]. These AI-driven tools support personalized treatment planning and patient management through predictive analytics and tailored preventive strategies[24, 25]. Meanwhile, nanotechnology offers innovative therapeutic approaches by enabling precise detection of periodontal pathogens, localized delivery of antimicrobial agents, and regenerative treatment of periodontal tissues such as cementum, periodontal ligament, and bone[26, 27]. Nanoparticles like liposomes and quantum dots enhance treatment efficacy while minimizing side effects compared to conventional therapies[26, 27].

The synergy between AI and nanotechnology in periodontics is evident in case studies that showcase their complementary roles in improving

diagnosis, predicting disease progression, and optimizing therapeutic interventions. AI-driven models enable more effective and personalized care, while nanotechnology provides targeted, controlled treatments, leading to better patient outcomes and more efficient resource use. These combined technologies hold great promise for advancing evidence-based periodontal care, ultimately revolutionizing disease management and enhancing long-term oral health[24, 26, 28].

IMPACT ON ORTHODONTICS

The integration of AI and nanotechnology in orthodontics is revolutionizing the field by enhancing treatment planning, improving material performance, and paving the way for personalized care. AI is being utilized to optimize treatment strategies and monitor patient progress in real-time, while nanotechnology is advancing the development of orthodontic materials and appliances. These innovations are not only improving the efficiency and accuracy of orthodontic treatments but also offering new possibilities for personalized care. The following sections delve into the specific impacts of AI and nanotechnology on orthodontics.

AI technologies, such as machine learning and deep learning, are transforming orthodontic treatment planning by enabling analysis of complex datasets to predict patient-specific treatment outcomes and optimize strategies [29]. AI algorithms facilitate automated cephalometric analysis, increasing diagnostic accuracy while minimizing human error [30]. Furthermore, AI-powered real-time monitoring systems support remote tracking of patients' progress, reducing the necessity for frequent office visits and thereby improving patient compliance [31]. Virtual treatment simulations driven by AI allow patients to visualize anticipated results, promoting informed decision-making and tailoring treatment plans to individual needs [30]. These advancements underscore AI's pivotal role in enhancing the precision, personalization, and efficiency of orthodontic care.

Nanotechnology is increasingly being applied in orthodontics to develop advanced materials such as nanocomposites and nano-coated wires and brackets, which improve mechanical strength and reduce friction in orthodontic appliances [32, 33]. The integration of antimicrobial agents within nanosolutions contributes to the prevention of white spot lesions and promotes better oral hygiene during orthodontic treatment. Additionally, smart materials and nanosensors are being explored to provide real-time feedback on treatment progress, potentially enhancing both the effectiveness and comfort of orthodontic care [33]. These innovations demonstrate the promising role of nanotechnology in improving the outcomes and patient experience in orthodontics.

The future of orthodontics is poised for significant advancements through the integration of AI with robotics and 3D printing technologies, enabling the execution of precise procedures and the fabrication of personalized orthodontic devices [31]. By leveraging extensive datasets, AI holds the potential to facilitate predictive orthodontics, supporting early interventions and more customized treatment protocols tailored to individual patient profiles [34]. Concurrently, nanotechnology is anticipated to drive the development of smart materials capable of adapting to the unique requirements of each patient, thereby further enhancing the personalization and effectiveness of orthodontic care [33]. These technological convergences are set to revolutionize treatment outcomes, increasing both precision and patient comfort.

While AI and nanotechnology are transforming orthodontics, challenges such as data privacy, algorithmic bias, and the cost of technology adoption remain significant hurdles[31, 35]. Addressing these issues is crucial for the ethical and effective implementation of these technologies in clinical practice. As research and development continue, the potential for AI and nanotechnology to revolutionize orthodontic care and improve patient outcomes is immense, promising a future of more efficient, personalized, and accessible treatments.

ROLE IN ORAL AND MAXILLOFACIAL SURGERY

The integration of AI and nanotechnology in oral and maxillofacial surgery (OMFS) is revolutionizing surgical procedures, enhancing precision, and improving patient outcomes. AI-driven surgical planning and robotic-assisted procedures are at the forefront of this transformation, offering unprecedented accuracy and efficiency. Concurrently, nanotechnology is making strides in tissue engineering, wound healing, and infection control, further augmenting surgical success. Together, these innovations are setting new standards in surgical outcomes,

promising a future where technology and clinical practice are seamlessly integrated.

AI technologies are having a transformative impact on OMFS, with applications spanning from advanced image analysis to surgical planning and intraoperative guidance, all contributing to more accurate diagnoses and greater surgical precision[36]. AI-driven tools enable surgeons to meticulously plan procedures in advance and provide real-time navigation during surgery, making it easier to safely navigate complex anatomical structures and reduce operative errors[37]. The integration of robotics powered by AI allows for highly intricate procedures to be performed with exceptional accuracy, minimizing human error and often leading to quicker recovery times for patients[38]. Despite some ongoing challenges, such as data quality and the need for robust clinical validation, the potential of AI-enhanced surgical planning and robotic assistance to elevate outcomes across OMFS procedures is increasingly evident and continues to evolve with further research and technological developments.

Nanotechnology holds great promise in tissue engineering by providing innovative solutions for regenerating damaged tissues and accelerating wound healing. Advanced nanomaterials such as nanofibers and nanocomposites mimic the natural extracellular matrix, facilitating cellular growth and differentiation while improving vascularization and tissue integration [39, 40]. Additionally, the antimicrobial properties of nanoparticles contribute significantly to infection control in surgical settings, reducing the risk of postoperative complications. Together with AI-driven surgical innovations, these advancements in nanotechnology are poised to substantially improve surgical outcomes and patient care, enabling more personalized and effective treatment approaches [39].

The integration of AI and nanotechnology is markedly improving surgical outcomes across oral and maxillofacial surgery by enhancing diagnostic accuracy, streamlining surgical planning, and optimizing postoperative care. AI-powered models now deliver high accuracy in predicting surgical risks, such as estimated blood loss and the likelihood of postoperative swelling, supporting better perioperative management and more individualized care[41]. The convergence of AI with nanotechnology is enabling new frontiers in the field, as innovations like AI-driven robotic surgery and nanomaterial-based tissue engineering advance the safety, precision, and effectiveness of surgical interventions. These technological developments collectively set the stage for safer, more predictable, and patient-centered approaches within OMFS[38, 39].

While the integration of AI and nanotechnology in OMFS is promising, it is essential to address the challenges associated with these technologies. Issues such as data privacy, regulatory compliance, and the need for ongoing training for clinicians are critical considerations[42]. Additionally, the current evidence supporting these technologies is often constrained by methodological weaknesses and limited validation, highlighting the need for further research and development[41]. Despite these challenges, the potential of AI and nanotechnology to transform surgical practices and improve patient outcomes remains significant, warranting continued exploration and investment in these fields. Table 1 summarizes the critical advancements in artificial intelligence and nanotechnology applications across key dental fields, illustrating the depth and breadth of their transformative impact supported by relevant studies.

CHALLENGES AND ETHICAL CONSIDERATIONS

The integration of AI and nanotechnology in implant dentistry, periodontology, orthodontics, and surgical procedures presents numerous challenges and ethical considerations. These challenges include data limitations, cost, accessibility, and training requirements, as well as ethical concerns such as patient privacy and algorithmic biases. Addressing these issues is crucial for the responsible and effective implementation of these technologies in dental practice.

The adoption of AI and nanotechnology in dental practices faces several notable challenges. One major limitation lies in the scarcity of high-quality and standardized datasets that are essential for training robust and generalizable AI models across diverse populations and clinical settings [35]. Additionally, the implementation costs can be prohibitive, as initial investments in AI and nanotech infrastructure, software, and ongoing maintenance often exceed the budgets of smaller dental practices [43]. Accessibility also remains uneven, creating disparities in advanced dental care between urban and rural locations and

Table 1. Key applications of artificial intelligence and nanotechnology in various dental specialties

Application Area	Key Advances	References
Implant Dentistry	AI-assisted implant planning, predictive modeling, nanocoated implant surfaces enhancing osseointegration	1, 2, 4, 15, 16
Periodontology	AI for early disease detection and risk classification; nanoparticles for targeted antimicrobial delivery and tissue regeneration	18, 20, 22, 23
Orthodontics	AI-driven treatment optimization and remote monitoring; nanomaterials improving appliance strength and reducing friction	25, 27, 28, 29
Oral and Maxillofacial Surgery	AI-enhanced surgical planning and robotic assistance; nanofibers and nanoparticles for tissue engineering and infection control	32, 34, 35, 36

between developed and developing regions [44]. Furthermore, effective use of these technologies demands comprehensive training programs for dental professionals, emphasizing the need to equip practitioners with the skills required to fully leverage AI in clinical workflows [45, 46]. Addressing these barriers is crucial to realizing the full potential of AI and nanotechnology in enhancing dental healthcare delivery.

The integration of AI in dentistry introduces critical concerns regarding patient privacy and data security, requiring strict adherence to data protection regulations such as HIPAA and GDPR to ensure the confidentiality of sensitive patient information[47, 48]. Additionally, if AI systems are trained on nonrepresentative datasets, algorithmic biases can emerge, potentially leading to disparities in treatment recommendations and outcomes across different populations[46, 47]. As practitioners increasingly rely on AI-powered tools, questions arise about maintaining professional autonomy and clarifying accountability when errors or adverse outcomes occur[44]. To address these challenges, there is a pressing need for robust regulatory and ethical frameworks that mandate informed consent, transparency, and clear legal responsibilities for the use of AI in dental settings. These frameworks are essential to promote trustworthy and equitable AI adoption in dentistry while upholding high standards of patient-centered care[47, 49].

While the integration of AI and nanotechnology in dentistry offers significant potential for improving diagnostic accuracy, treatment planning, and patient outcomes, it is essential to address the associated challenges and ethical considerations. Ensuring equitable access to these technologies, protecting patient privacy, and mitigating algorithmic biases are critical for their successful implementation. Additionally, fostering interdisciplinary collaboration and developing comprehensive training programs for dental professionals will be vital in overcoming these challenges and maximizing the benefits of AI and nanotechnology in dental care.

CONCLUSION, FUTURE DIRECTIONS AND EMERGING TRENDS

The integration of AI and nanotechnology across key dental specialtiesimplant dentistry, periodontology, orthodontics, and surgerymarks a major leap forward in dental care, enabling transformative changes in diagnostics, treatment planning, and patient management that yield improved clinical outcomes and greater patient satisfaction. AI excels in diagnostic imaging, routinely surpassing traditional methods in caries detection, periodontal assessment, and image-guided planning, thereby delivering heightened accuracy and personalized treatment strategies. Advances in nanotechnology have elevated dental biomaterials, with innovations such as nanostructured implant surfaces significantly enhancing osseointegration, stability, and comfort for patients. Automated planning and predictive modeling facilitated by AI optimize workflows and empower practitioners to deliver tailored care efficiently.

Despite these revolutionary developments, several challenges persist. Transparency issues, data bias, privacy concerns, and questions of legal and ethical responsibility remain critical hurdles to safe, equitable adoption of these technologies. Moving forward, a focus on multimodal data integration

will be vital in supporting precision dentistry, while synergistic advances in regenerative therapies and 3D printing promise even more sophisticated treatment options. For these innovations to have broad impact, increased attention must be paid to cost-effectiveness, accessibility in underserved regions, and the establishment of robust regulatory and ethical standards.

Emerging trends include the rise of AI-driven precision dentistry leveraging digital twins, smart dental tools for enhanced patient monitoring, robotic-assisted surgery for unprecedented accuracy, and interdisciplinary collaboration that bridges clinical, research, and technological domains. Importantly, while AI and nanotechnology are reshaping the field, they complement rather than substitute for the clinical judgment and empathy provided by dental professionals. The future of dentistry will depend on finding the right balance between technological innovation and human expertise to realize the full benefits of these advances.

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CONFLICT OF INTEREST

The authors declare that there are no conflicts of interest related to the research, authorship, or publication of this manuscript. All authors have disclosed any financial or personal relationships that could potentially influence or bias the work presented.

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