

REVIEW ARTICLE

## Nanorobots and Smart Nanodevices with Artificial Intelligence for Precision Orthodontic Surgery and Treatment Monitoring

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### ABSTRACT

The convergence of nanorobotics, smart nanodevices, and artificial intelligence (AI) heralds a new era in precision orthodontic surgery and treatment monitoring. Nanorobots, operating at the cellular level, enable minimally invasive, highly accurate interventions such as targeted drug delivery, tooth repair, and orthodontic adjustments, significantly reducing patient discomfort and recovery time. The integration of AI enhances these capabilities by enabling real-time data analysis, predictive treatment planning, and continuous monitoring, which not only optimizes clinical outcomes but also improves operational efficiency and patient engagement. Smart nanodevices embedded with advanced sensors facilitate precise measurement of orthodontic forces and remote data transmission, supporting personalized treatment adjustments and remote patient monitoring. Despite challenges in fabrication, biocompatibility, regulatory approval, and ethical concerns such as data privacy, ongoing advancements suggest a transformative potential for these technologies in orthodontics. This review explores the current state, applications, challenges, and future directions of AI-integrated nanorobotics and smart nanodevices in orthodontic practice, highlighting their promise for revolutionizing patient care through precision, personalization, and enhanced treatment efficacy.

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## INTRODUCTION

The integration of nanorobots and smart nanodevices in healthcare represents a significant advancement in medical technology, particularly in the field of orthodontics. These microscopic devices, operating at the nanoscale, offer unprecedented precision and control in medical interventions, promising to revolutionize

traditional dental practices. The convergence of nanotechnology with artificial intelligence (AI) further enhances the capabilities of these devices, enabling precision surgery and real-time treatment monitoring. This review paper aims to explore the transformative potential of nanorobots and smart nanodevices, particularly in orthodontics, and the role of AI in enhancing their functionality.

Nanorobots are designed to perform complex

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tasks at the cellular level, offering precise interventions in orthodontic procedures. They can be used for tasks such as tooth repair, drug delivery, and orthodontic adjustments, providing swift and accurate dental care interventions [1, 2]. The use of nanorobots in orthodontics allows for minimally invasive procedures, reducing patient discomfort and recovery time. These devices can navigate through human tissue with precision, ensuring safe and effective treatment outcomes [3, 4]. By integrating AI, nanorobots can analyze complex data to optimize treatment strategies, leading to improved patient outcomes. AI-driven systems support orthodontists in making informed decisions, particularly in treatment planning and monitoring [5, 6].

AI technologies, including machine learning and deep learning, facilitate the automated analysis of complex data, aiding in precise diagnosis and efficient treatment strategies. This reduces human error and personalizes treatment plans, ultimately leading to better patient care [6, 7]. AI enhances post-treatment monitoring by continuously analyzing data and providing feedback, ensuring timely interventions and improving recovery. This empowers both patients and practitioners with proactive insights into sustained oral health [5]. The fusion of AI with robotics in dentistry enhances surgical precision and control, resulting in superior outcomes and quicker recovery times for patients. AI algorithms streamline procedures, optimize scheduling, and enhance patient experience, thereby improving overall operational efficiency [5, 7].

The primary objective of this review paper is to explore the applications and benefits of integrating nanorobots and smart nanodevices with AI in orthodontics. It aims to highlight the potential of these technologies in enhancing precision surgery and treatment monitoring. The review will cover the current state of research on nanorobots and AI in orthodontics, their applications, and the challenges associated with their integration. It will also discuss future prospects and the potential for these technologies to revolutionize orthodontic practices.

## **BACKGROUND AND FUNDAMENTALS OF NANOROBOTICS AND SMART NANODEVICES**

Nanorobots are designed to operate at nanoscale dimensions. These devices can navigate

through human tissues with precision, enabling tasks such as destroying caries-causing bacteria or repairing teeth with hypersensitivity. The potential for nanorobots to perform high-precision dental treatments with minimal invasiveness is significant, offering benefits like painless and quick procedures [1, 8]. In orthodontics, nanotechnology facilitates advanced diagnostics, targeted drug delivery, and the development of biomaterials. It enables precise orthodontic tooth movement and enhances the effectiveness of treatments like local anesthesia. The use of nanomaterials with shape memory properties allows for more efficient tooth movement, reducing treatment times and improving patient outcomes [9-11]. Ag/ZnO nanocomposite exhibits a high antibacterial activity against the dental caries-causing pathogen *Streptococcus mutans* by disrupting bacterial membrane function and inducing oxidative stress, while maintaining low cytotoxicity toward mammalian cells, making it a promising candidate for dental applications [12]. AI enhances the capabilities of nanorobots by improving navigation, predictive analytics, and personalized treatment plans. This integration allows for real-time monitoring and adjustments during orthodontic procedures, ensuring optimal results. AI-driven nanorobots can adapt to the dynamic conditions within the oral cavity, providing a tailored approach to each patient's needs [13, 14].

Nanorobots enable minimally invasive surgical procedures with high precision, reducing collateral damage and expediting recovery. In orthodontics, this precision is crucial for aligning teeth accurately and efficiently, minimizing the risk of complications and enhancing the overall treatment experience [4, 15]. The ability to monitor treatment progress in real-time is a significant advantage of using nanorobots and AI in orthodontics. This capability allows for immediate adjustments to treatment plans, ensuring that interventions are effective and aligned with the desired outcomes. Real-time monitoring also enhances patient safety by allowing for the early detection of potential issues [13, 16].

## **NANOROBOTS IN ORTHODONTIC SURGERY**

Nanorobots are designed at the molecular scale, enabling them to interact with biological systems at the cellular level. This design allows for precise interventions in orthodontic procedures, such as

targeted drug delivery and minimally invasive surgeries [17, 18]. These nanorobots are powered by various energy sources, including chemical reactions and external magnetic fields, which facilitate their movement and operation within the human body. Propulsion methods are critical for navigating complex biological environments[17]. Incorporating artificial intelligence, these devices can perform complex tasks autonomously, such as monitoring treatment progress and adjusting interventions in real-time. This capability enhances the precision and effectiveness of orthodontic treatments [19, 20].

Nanorobots can deliver drugs directly to specific sites, reducing systemic side effects and increasing treatment efficacy. This is particularly beneficial in orthodontics for managing inflammation and infection control [18, 21]. The ability of nanorobots to perform surgeries at the nanoscale reduces the need for large incisions, leading to faster recovery times and reduced risk of complications. This is a significant advancement in orthodontic surgical procedures [17, 18].

Smart nanodevices equipped with sensors can monitor orthodontic forces and moments in real-time, providing valuable data for optimizing treatment plans and ensuring patient safety [20].

Nanorobots enhance the precision of orthodontic surgeries by providing detailed imaging and analysis of treatment areas. This allows for more accurate placement of orthodontic devices and improved surgical outcomes [22, 23]. The integration of nanotechnology in orthodontics facilitates continuous monitoring of treatment progress, enabling timely adjustments and improving overall treatment efficacy [19, 20]. Various studies have demonstrated the effectiveness of nanorobots in improving orthodontic treatment outcomes, such as reducing friction in orthodontic wires and enhancing the bonding of orthodontic appliances [9, 23].

## SMART NANODEVICES FOR TREATMENT MONITORING

The development and application of smart nanodevices in orthodontics have revolutionized the monitoring of treatment progress, offering enhanced precision and personalization. These devices integrate advanced sensors, data acquisition methods, and communication technologies to provide real-time feedback on orthodontic treatment, enabling more effective

and personalized adjustments. The integration of nanotechnology and AI in orthodontics has paved the way for innovative solutions that improve patient compliance and treatment outcomes. This section will explore the types of sensors used, data acquisition methods, communication technologies, and the role of these smart devices in personalized treatment adjustments.

Piezosensors are integrated into orthodontic appliances to measure forces and moments applied to teeth, providing critical data for treatment monitoring[24, 25]. These sensors are embedded in smart brackets to detect 3D force and moment vectors, offering precise measurements of tooth movement and stress distribution[26]. These sensors can detect all six components of force and moment, providing comprehensive feedback on the forces applied during orthodontic treatment[25].

Smart brackets equipped with telemetric systems allow for the remote collection of sensor data, which is then transmitted to a reader unit for analysis[26]. Sensors embedded in orthodontic appliances provide continuous data on tooth movement and forces, enabling real-time monitoring and adjustments[27, 28]. AI algorithms process the data collected from sensors to simulate tooth movements, predict treatment outcomes, and optimize treatment sequences[29].

Communication technologies have significantly advanced the field of orthodontics. The Internet of Dental Things (IoDT) enables the seamless integration of smart orthodontic devices with digital networks, allowing orthodontists to remotely monitor patients and share data efficiently[30]. Additionally, Radio Frequency Identification (RFID) systems are employed in telemetric smart brackets to facilitate contactless data transmission, thereby improving the effectiveness and ease of data acquisition and communication within orthodontic care[26].

Smart devices play a crucial role in personalized treatment adjustments in orthodontics. Real-time data collected from these devices enable orthodontists to make precise modifications to treatment plans, enhancing the accuracy and effectiveness of care[30]. Furthermore, by offering detailed feedback on treatment progress, smart devices promote patient compliance and engagement, which contributes to improved outcomes[31]. Remote monitoring capabilities reduce the necessity for frequent in-person appointments, making orthodontic care more

accessible and convenient for patients[30]. Despite these advantages, challenges such as the complexity and cost of these technologies may hinder widespread adoption. Continued research is essential to improve the reliability and safety of these systems. Additionally, ethical issues related to data privacy and security need careful attention as smart nanodevices become increasingly integrated into orthodontic practice. Nonetheless, their potential to revolutionize orthodontic treatment by providing more personalized and effective care is substantial. Table 1 summarizes the key features, applications, and benefits of nanorobots, smart nanodevices, and AI as integrated technologies in advancing precision orthodontic treatments.

**ARTIFICIAL INTELLIGENCE INTEGRATION**

The integration of AI with nanorobots and smart nanodevices is revolutionizing precision orthodontic surgery and treatment monitoring. Artificial intelligence demonstrates comparable or superior accuracy to clinicians, highlighting its potential to enhance diagnostic precision and surgical planning in oral healthcare [32]. AI enhances the capabilities of these devices by enabling precise control, real-time data analysis, and predictive modeling, which are crucial for personalized and effective treatment strategies. This integration leverages machine learning algorithms, data analysis, and decision support systems to facilitate precision treatment and monitoring, offering significant improvements in patient outcomes and healthcare efficiency. The following sections explore the key aspects of AI integration in nanorobots and smart nanodevices. Intelligent optimization algorithms play a crucial role in enhancing sentiment analysis by improving the efficiency and accuracy of data processing, which can be effectively translated into optimizing

treatment monitoring and patient feedback mechanisms in orthodontic care[33].

Machine learning (ML) algorithms play a critical role in analyzing complex medical datasets, enabling the identification of patterns that traditional methods might overlook. This capability facilitates the creation of precision-based treatment strategies tailored to the unique needs of each patient[34]. In the realm of nanorobotics, ML algorithms can be employed to train nanorobots for specialized tasks such as targeted drug delivery and real-time monitoring of treatment effectiveness, thereby significantly improving their accuracy and operational efficiency in medical applications[35].

AI-driven data analysis plays a vital role in continuously tracking physiological biomarkers, which is crucial for the early detection and precise monitoring of disease progression, especially in cancer diagnostics. By analyzing complex and multidimensional datasets, AI models can uncover biomarker signatures that enhance diagnostic precision and enable earlier interventions, ultimately improving patient outcomes[36]. Furthermore, predictive modeling powered by AI integrates diverse data sources, including patient demographics, medical history, and genetic information, to develop personalized treatment plans with high predictive accuracy. This approach allows clinicians to optimize therapeutic strategies by accurately forecasting patient responses, thereby enhancing treatment effectiveness[34].

AI-powered decision support systems significantly enhance clinical decision-making by integrating and analyzing data from electronic health records (EHRs) and other diverse sources in real time. These systems offer valuable insights that support proactive healthcare interventions and enable clinicians to optimize treatment strategies[34].In surgical contexts, AI-driven decision support tools improve the precision and

Table 1. Overview of nanorobots, smart nanodevices, and AI applications in orthodontics, highlighting their features and benefits

Technology Component	Key Features	Applications in Orthodontics	Benefits
Nanorobots	Nanoscale operation, targeted delivery	Tooth repair, drug delivery, minimally invasive surgery	Precision interventions, reduced recovery time
Smart Nanodevices	Embedded sensors, telemetric data transfer	Real-time force and moment monitoring, remote patient monitoring	Personalized treatment adjustments, improved patient compliance
Artificial Intelligence	Machine learning, predictive modeling	Treatment planning, real-time data analysis, outcome prediction	Enhanced diagnostic accuracy, optimized treatment, decision support



efficiency of robotic surgeries by reducing human error and contributing to faster patient recovery[34, 37].

The integration of AI with nanotechnology is advancing precision medicine by enabling treatment plans tailored to the unique characteristics of each patient. This approach is especially effective for managing chronic and complex conditions, where personalized strategies can significantly enhance outcomes[38]. Smart nanodevices equipped with AI capabilities provide unprecedented precision in detecting and monitoring disease markers, resulting in more accurate diagnostics and bespoke treatment plans[36, 39]. AI optimizes the design and function of nanosensors and nanorobots, facilitating targeted drug delivery, early disease detection, and real-time monitoring of therapeutic efficacy. However, challenges such as data privacy, ethical concerns, and technical limitations must be addressed for responsible implementation. Developing robust regulatory frameworks and fostering interdisciplinary collaboration are essential to harness the full potential of AI-driven nanotechnologies in healthcare, particularly in precision orthodontic surgery and treatment monitoring.

## CHALLENGES AND LIMITATIONS

The integration of nanorobots and smart nanodevices with AI in precision orthodontic surgery and treatment monitoring presents a promising frontier in medical technology. However, this field faces several challenges and limitations that need to be addressed to realize its full potential. These challenges span technical, ethical, and regulatory domains, and include issues related to device fabrication, biocompatibility, data security, and integration into clinical practice. Below, these challenges and limitations are explored in detail.

The fabrication of nanorobots involves complex processes that require precision at the nanoscale. This complexity can lead to high production costs and difficulties in achieving consistent quality and functionality across devices[3]. Ensuring that nanorobots are biocompatible is crucial to prevent adverse reactions within the human body. This involves addressing potential toxicity and immune responses, which remain significant hurdles in the development of these devices[3, 21].

Scaling up the production of nanorobots for widespread clinical use is challenging due to the intricate manufacturing processes and the need for

specialized materials[3].

The use of AI and nanotechnology in medicine raises ethical questions, particularly regarding patient autonomy and consent. There is a need for clear guidelines to ensure that these technologies are used responsibly[40]. Obtaining regulatory approval for nanorobots is a complex process that involves demonstrating safety and efficacy. The lack of established regulatory frameworks for these novel technologies can delay their clinical adoption[3, 41].

AI systems in orthodontics rely on large datasets, which raises concerns about data security and patient privacy. Ensuring the protection of sensitive patient information is paramount to gaining trust and compliance from both patients and practitioners[42]. Integrating AI-driven nanorobots into existing healthcare systems requires robust data management and interoperability solutions to ensure seamless operation and data exchange[40].

The successful integration of nanorobots into clinical practice requires healthcare professionals to acquire new skills and knowledge. This necessitates comprehensive training programs to overcome the steep learning curve associated with these advanced technologies. The high cost of developing and implementing nanorobotic systems can limit their accessibility, particularly in resource-constrained settings. Efforts to reduce costs and improve affordability are essential for widespread adoption[40]. While the challenges and limitations in the field of nanorobots and smart nanodevices for orthodontic applications are significant, they are not insurmountable. Addressing these issues requires a collaborative approach involving researchers, clinicians, policymakers, and industry stakeholders. By focusing on overcoming technical barriers, establishing ethical and regulatory frameworks, and ensuring data security, the potential of these technologies to transform orthodontic care can be realized. Additionally, ongoing research and development efforts are crucial to refining these technologies and expanding their applications in clinical practice.

## FUTURE DIRECTIONS AND TRENDS

The integration of nanorobotics, smart devices, and AI in orthodontics is poised to revolutionize the field by enhancing precision, efficiency, and patient outcomes. Future advancements are expected to focus on improving materials, AI sophistication,

autonomous systems, and patient-centered technologies. These innovations will likely lead to more personalized and effective orthodontic treatments, with significant implications for both practitioners and patients.

The use of nanomaterials in orthodontics is anticipated to significantly enhance the performance of orthodontic devices, with nanocoatings applied to brackets and wires shown to reduce friction, thereby accelerating tooth movement and improving overall treatment efficiency. This aligns with advancements reported in related dental fields, where green-synthesized metal and metal oxide nanoparticles have demonstrated improved material properties and biocompatibility in dental implant applications, suggesting promising potential for similar benefits in orthodontic device enhancement[19, 23, 43]. Shape-memory polymers and other smart materials are being explored for their potential to improve the adaptability and responsiveness of orthodontic devices, allowing for more precise control over tooth movement[23].

Emerging therapeutic approaches for oral cavity squamous cell carcinoma (OCSCC) are increasingly focusing on targeting molecular pathways such as EGFR overexpression and leveraging nanoengineered drug delivery systems to enhance treatment efficacy while minimizing systemic toxicity[44].

AI is already being used to analyze dental images with high accuracy, and future developments are expected to further refine these capabilities, enabling even more precise diagnoses and treatment planning[5, 29]. AI algorithms are anticipated to become more sophisticated, allowing for better prediction of treatment outcomes and optimization of treatment sequences, which will enhance personalized care[29].

Nanorobots are being developed to perform complex tasks such as drug delivery and tissue manipulation with high precision. In orthodontics, they could be used for tasks like tooth repositioning and periodontal tissue manipulation, offering minimally invasive treatment options[45-47]. The integration of robotics in orthodontics is expected to enhance surgical precision and reduce recovery times, with robots performing tasks such as drilling and shaping with unparalleled accuracy[5].

AI-powered systems are facilitating remote monitoring of patient progress, which can improve treatment adherence and allow for timely interventions. This trend is expected to

grow, making orthodontic care more accessible and convenient[29]. The combination of AI and nanotechnology will enable the creation of highly personalized treatment plans, tailored to the specific needs and conditions of each patient, thereby improving overall treatment outcomes[5, 29].

While these advancements hold great promise, it is important to consider the challenges and ethical considerations associated with their implementation. Issues such as data security, patient privacy, and regulatory approval must be addressed to ensure the safe and effective integration of these technologies into orthodontic practice. Additionally, the cost and accessibility of these advanced treatments may pose barriers that need to be overcome to ensure equitable access for all patients. As the field continues to evolve, collaboration among researchers, clinicians, and policymakers will be crucial in navigating these challenges and harnessing the full potential of these emerging technologies.

## CONCLUSION

The integration of nanorobots, smart nanodevices, and AI in precision orthodontic surgery and treatment monitoring marks a significant advancement in dental healthcare, offering enhanced accuracy, efficiency, and personalized care. Robotics and AI have revolutionized orthodontic practices by improving diagnostic precision, optimizing treatment planning, and enhancing patient outcomes through greater dexterity and control during procedures, which leads to quicker recovery times. Nanorobots, positioned at the intersection of nanotechnology and robotics, provide transformative capabilities such as targeted drug delivery and individualized treatment adjustments, crucial for applications like tooth repair and orthodontic correction. The synergy between AI and smart technologies further advances these developments by reducing human error, increasing surgical precision, and enabling continuous remote monitoring of treatment progress, which proves especially valuable for patients in remote or underserved areas. This convergence also allows for the creation of personalized treatment plans through AI algorithms that analyze large datasets, tailoring interventions to each patient's unique needs. However, to fully realize these benefits, ongoing research must address technological challenges, regulatory and

safety considerations, and ethical issues including data privacy and algorithmic bias. Interdisciplinary collaboration among researchers, clinicians, technologists, and policymakers is essential to foster responsible innovation and smooth integration of AI and nanorobotics into clinical orthodontic practice. While the potential of these technologies is immense, addressing readiness and ethical concerns remains crucial to advancing the field and improving patient care in a sustainable and equitable manner.

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#### CONFLICT OF INTEREST STATEMENT

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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