REVEIW ARTICLE

# Periodontal, Implant, and Oral Medicine: Nanoscale Innovations in Radiology and Imaging

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**ABSTRACT**

Nanoscale innovations are transforming radiology and imaging in periodontal, implant, and oral medicine by enabling earlier, more precise, and personalized diagnosis. This review summarizes key nanoscale contrast agents, including silica nanoparticles, carbon nanotubes, gadolinium-based nanostructures, quantum dots, and gold nanoparticles, and their roles in enhancing MRI, CT, CBCT, OCT, and nano-CT imaging performance. Applications in periodontal diagnostics, implantology, and oral medicine are highlighted, such as nano-probes for biofilm and inflammatory marker detection, nano-engineered implant surfaces, and nano-enabled strategies for oral cancer and mucosal lesions. The review also outlines how integration with artificial intelligence, including deep learning-based image analysis and emerging Nano-AI theranostic platforms, can further improve diagnostic accuracy and treatment planning while emphasizing current challenges related to safety, regulation, cost, and ethical considerations.

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## INTRODUCTION

Periodontal diseases, implant failures, and oral pathologies impose a major global burden on dental health, affecting millions and often leading to tooth loss or systemic complications [1-3]. Periodontal diseases involve inflammation and destruction of tooth-supporting structures, while peri-implantitis remains a leading cause of implant failure. Oral pathologies such as infections and cancers demand highly precise diagnostic tools for effective management [3,4]. Although conventional imaging methods like cone beam computed tomography (CBCT) and panoramic X-rays play a key role in diagnosing these conditions, they face limitations including insufficient resolution for early detection, beam-hardening artifacts, and higher radiation exposure, all of which reduce diagnostic accuracy [5].

Recent advances in nanotechnology, particularly the use of quantum dots and gold nanoparticles, have shown great potential in overcoming these diagnostic challenges. Quantum dots enhance image resolution and contrast at the molecular level [2,6], while gold nanoparticles improve imaging specificity and enable targeted visualization

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of oral tissues[3]. Together, these nanoscale innovations could significantly improve the early detection, characterization, and management of periodontal and peri-implant diseases. However, their integration into dental practice must consider potential health, environmental, and ethical concerns, as well as cost and accessibility, to ensure safe and equitable adoption of these technologies. The key thematic domains and their representative applications are summarized in Table 1.

## NANOSCALE MATERIALS IN DENTAL IMAGING

Nanoscale materials have become crucial in advancing dental imaging by enhancing contrast and resolution in modalities such as magnetic resonance imaging (MRI), computed tomography (CT), and optical coherence tomography (OCT). Their unique physicochemical properties enable superior image clarity and diagnostic precision, making them valuable tools for visualizing dental structures with high spatial definition. Among these, silica nanoparticles, carbon nanotubes, and gadolinium-based agents are particularly noteworthy due to their tunable surface chemistry, radiopacity, and potential for multifunctional applications such as simultaneous imaging and drug delivery. Silica nanoparticles, known for their versatility, can be doped or functionalized with elements like gadolinium, iron, or manganese to enhance MRI contrast, while maintaining good biocompatibility and low toxicity[7, 8]. Similarly, carbon nanotubes, especially gadonanotubes, demonstrate exceptional MRI performance because of their high relaxivity and ability to encapsulate gadolinium ions, achieving up to 100-fold greater efficacy than conventional contrast agents. They also facilitate cellular and molecular imaging, offering potential for targeted diagnostics and therapeutic use[9, 10].

Gadolinium-based nanostructures, including gadofullerenes and gadonanotubes, further enhance MRI imaging by delivering strong signal intensity and tissue-specific targeting at the molecular level, although their safety must be carefully managed due to possible nephrotoxic effects in susceptible patients[9, 10]. The radiopacity of silica and gadolinium-based nanoparticles significantly contributes to improved visibility of dental and peri-implant structures in CT and MRI, supporting early disease detection and treatment planning. Ensuring the biocompatibility of these materials remains fundamental for their successful clinical translation, as most exhibit low cytotoxicity and favorable biological interactions[7, 8, 11]. Collectively, these nanoscale agents represent a significant step forward in dental imaging innovation, offering integrated approaches that combine diagnostic precision with therapeutic potential.

## APPLICATIONS IN PERIODONTAL DIAGNOSTICS

The convergence of nanoscale innovations and artificial intelligence (AI) has transformed periodontal diagnostics, enabling earlier and more precise detection of periodontitis and alveolar bone loss. Nano-probes designed for biofilm imaging and inflammation marker targeting, combined with AI-driven radiographic analysis, represent the forefront of these innovations. Together, they improve diagnostic accuracy, reduce human error, and facilitate timely interventions that enhance patient outcomes. These advanced tools are paving the way for predictive, personalized, and technology-assisted dental care.

Nano-probes offer significant advantages in detecting early pathological changes within periodontal tissues. Engineered to bind specific biofilm components and inflammatory biomarkers,

Table 1. Key application domains of nanotechnology in periodontal, implant, and oral medicine.

| Domain | Focus in this review | Representative examples |
|---|---|---|
| Nanoscale imaging agents | Enhancement of contrast, resolution, and molecular visualization in dental imaging | Silica NPs, carbon nanotubes, gadolinium nanostructures, quantum dots, AuNPs |
| Periodontal diagnostics | Early detection of biofilm, inflammation, and bone loss using nano/AI tools | Nano-probes for biomarkers; CNN-, YOLOv8-, MobileNet-v2–based analysis |
| Implantology | Nano-engineered surfaces and nano-enhanced imaging for osseointegration and peri-implantitis monitoring | Titania nanotubes, bioceramic coatings, nano-CT, nanoparticle tracers |
| Oral medicine and theranostics | Nano-enabled cancer/mucosal lesion imaging and targeted therapy | Gold nanomaterials, polymeric nanoagents, nanosensors, phototheranostics, nanocarriers |
| AI and Nano-AI platforms | Integration of AI with nano-imaging for prediction, super-resolution, and theranostics | Deep learning for segmentation, predictive analytics, Nano-AI theranostics |


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they provide high-resolution imaging of pathogenic bacterial activity and host responses. This molecular-level precision allows clinicians to identify disease at its inception, often before clinical symptoms manifest. In addition, their ability to detect subtle biochemical and structural changes contributes to more individualized treatment approaches based on a patient's inflammatory and microbial profile, offering the potential to prevent disease progression and improve therapeutic planning.

Simultaneously, AI-augmented analysis of radiographs has demonstrated remarkable progress in automating and refining periodontal assessment. Deep learning models, especially those based on convolutional neural networks (CNNs), can accurately segment dental structures, identify the cemento-enamel junction, and quantify alveolar bone levels with accuracies reported as high as 98% in certain studies[12]. Advanced frameworks like YOLOv8 and MobileNet-v2 have further improved classification of periodontitis severity and localization of affected regions, achieving testing accuracies up to 88%[13]. Beyond detection, AI systems can quantify bone defects and generate prognostic insights[14, 15], minimizing diagnostic variability and supporting data-driven treatment strategies that integrate seamlessly with nanoscale diagnostic technologies.

## NANOSCALE INNOVATIONS FOR IMPLANTOLOGY

Nanoscale innovations have profoundly influenced modern implantology, leading to substantial advancements in the performance, diagnosis, and longevity of dental implants. Through the development of nano-modified implant surfaces and integration with advanced imaging technologies, nanotechnology has enhanced osseointegration, facilitated early detection of peri-implantitis, and improved surgical navigation. These developments not only refine the physical and chemical characteristics of implant materials but also expand diagnostic precision at both micro- and nanoscale levels, thus significantly improving clinical success rates and patient outcomes.

Nano-engineered surface modifications play a pivotal role in optimizing implant performance. Nanostructured titanium, often enhanced with hydroxyapatite through plasma spraying, anodization, or coating techniques, mimics the natural bone microenvironment, promoting cellular adhesion and osseointegration[16, 17]. Similarly, titania nanotubes and bioceramic coatings increase surface energy and stimulate osteoblastic differentiation, thereby accelerating bone integration while offering intrinsic antibacterial properties to minimize peri-implant infections [18, 19]. Moreover, the use of nanoparticle-based antimicrobial and drug-delivery coatings enables controlled release of therapeutic agents at the implant site, ensuring localized infection control and long-term stability [20, 21].

Advanced imaging techniques have further augmented the assessment and clinical management of dental implants. Micro-CT and nano-CT allow high-resolution visualization of the bone–implant interface, providing quantitative data on osseointegration and bone density [22, 23]. Meanwhile, imaging systems enhanced with nanoparticle tracers enable early detection of peri-implantitis by identifying subtle inflammatory changes around the implant [24]. These same tracers are increasingly applied in surgical navigation, improving anatomical visualization and ensuring precise implant placement, thereby reducing procedural risks [25]. Collectively, these nanoscale and imaging-based innovations are reshaping implantology toward a more predictable, minimally invasive, and patient-tailored discipline.

## ADVANCES IN ORAL MEDICINE IMAGING

Recent advancements in oral medicine imaging have been significantly influenced by nanoscale innovations, which have broadened the scope of applications in oral health diagnostics and treatment. These innovations include the use of nanoscale contrast agents for oral cancer screening, enhanced visualization of mucosal lesions, and monitoring drug delivery in conditions like lichen planus or sialadenitis. The integration of nanotechnology in these areas promises to improve diagnostic accuracy and therapeutic outcomes, offering a more precise and less invasive approach to oral healthcare. The following sections explore these advancements in detail.

Gold nanoparticles (AuNPs) have gained significant attention in recent years for their role in oral cancer diagnosis, primarily due to their remarkable optical characteristics that allow for highly sensitive detection of cancer biomarkers using techniques such as surface-enhanced Raman spectroscopy (SERS) and surface plasmon resonance [26, 27]. Alongside these metallic


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nanostructures, polymeric nanoagents have emerged as promising tools for early and accurate cancer screening, offering superior biosafety and stability key factors that support their potential clinical application [26]. Furthermore, the development of phototheranostic nanoagents, which integrate phototherapeutic modalities with diagnostic imaging capabilities, has opened new avenues for precise, minimally invasive oral cancer detection and treatment [28].

Nanosensors, particularly biosensors, have been developed to detect small quantities of analytes, enabling the visualization of mucosal lesions with high sensitivity and specificity. These sensors can transduce physical, chemical, or biological signals into readable forms, facilitating early diagnosis [29-31]. The use of nanotechnology-enhanced photodynamic therapy (PDT) has been explored for the treatment of precancerous lesions, providing a non-invasive method to visualize and treat mucosal abnormalities [32].

Nanoparticle-based drug delivery systems have been designed to overcome the challenges of conventional drug administration in the oral cavity, such as constant salivary flow and drug resistance. These systems ensure targeted and controlled release of therapeutic agents, improving treatment efficacy for conditions like lichen planus and sialadenitis [33]. The integration of nanocarriers in drug delivery platforms allows for precise monitoring of drug release and distribution, enhancing the management of chronic oral conditions [2].

While the advancements in nanoscale imaging and diagnostics in oral medicine are promising, there are challenges and considerations that need to be addressed. The biocompatibility and long-term safety of nanoparticles remain a concern, as does the potential for unforeseen side effects. Additionally, the cost and complexity of developing and implementing these technologies may limit their accessibility and widespread adoption in clinical practice. Despite these challenges, the potential benefits of nanoscale innovations in improving oral health outcomes continue to drive research and development in this field.

## INTEGRATION WITH AI AND DIGITAL TECHNOLOGIES

The integration of AI and digital technologies in periodontal, implant, and oral medicine is revolutionizing radiology and imaging through nanoscale innovations. AI, particularly machine learning models like CNNs, is being trained on nano-enhanced datasets to automate processes such as segmentation, predictive analytics, and super-resolution imaging. These advancements are significantly enhancing the workflows in periodontal and implant dentistry by improving diagnostic accuracy, treatment planning, and patient outcomes. The following sections delve into the specific synergies and applications of AI in these fields.

AI models, especially CNNs, are being utilized for automated segmentation in dental imaging, which is crucial for identifying anatomical structures and diagnosing conditions such as periodontal disease and oral cancer [34, 35]. Intraoral imaging analysis in periodontics has been enhanced by AI, with models like DeepLabv3+ and U-Net demonstrating high accuracy in detecting gingivitis and dental plaque. These models are trained on large datasets, which are essential for improving the generalizability and precision of diagnostic outcomes [36].

AI-driven predictive analytics are transforming periodontal care by enabling early disease detection and personalized treatment planning [37]. Machine learning algorithms analyze vast datasets to predict disease progression and treatment outcomes, optimizing patient care and facilitating personalized interventions [38]. In implant dentistry, AI predicts implant failure rates and aids in detecting complications, thereby improving treatment accuracy and patient outcomes [39].

AI technologies are enhancing imaging resolution, allowing for more detailed visualization of dental structures, which is critical for accurate diagnosis and treatment planning [35]. Super-resolution imaging, powered by AI, provides clinicians with enhanced images that surpass the capabilities of traditional imaging techniques, leading to better clinical decision-making [40].

Despite the advancements, challenges such as data scarcity, annotation complexity, and model interpretability remain significant hurdles in the integration of AI in dental imaging [34]. Continuous validation and adaptation of AI models are necessary to ensure their accuracy and relevance in clinical practice [36]. Future research should focus on expanding dataset diversity, enhancing model robustness, and addressing ethical considerations to fully exploit AI's potential in periodontology and implant dentistry.

While AI and digital technologies are

revolutionizing periodontal and implant workflows, it is crucial to address the challenges associated with their integration. Ethical considerations, data privacy, and the need for interdisciplinary collaboration are essential to navigate the complexities of AI adoption in clinical practice. As AI continues to evolve, its potential to transform dental care through enhanced diagnostics, personalized treatment, and improved patient outcomes remains promising.

## CLINICAL EVIDENCE AND CASE STUDIES

The application of nanotechnology in radiology, particularly in cancer treatment, has shown promising results in enhancing efficacy, sensitivity, and specificity of imaging and therapeutic interventions. Clinical studies and trials have demonstrated the potential of nanoparticles (NPs) to improve drug delivery, enhance radiotherapy, and provide better imaging contrast, ultimately leading to improved patient outcomes. This synthesis will explore key studies, trials, and meta-analyses that highlight these advancements.

Advances in nanomedicine have significantly influenced cancer treatment strategies, particularly through the development of targeted drug delivery and radiation enhancement approaches. Clinical studies have underscored the vital role of imaging in evaluating nanomedicine-based drug delivery systems, confirming the enhanced permeability and retention (EPR) effect within tumor tissues a key mechanism facilitating the accumulation and uptake of therapeutic nanomaterials. This process has been directly linked to improved antitumor efficacy, demonstrating the potential of image-guided drug delivery for personalized treatment optimization [41, 42]. In parallel, nanoparticles have been applied as radiation nanosensitizers to amplify the therapeutic impact of radiotherapy. Clinical investigations have shown that these nanosensitizers can enhance the spatial precision of radiation, minimizing damage to surrounding healthy tissues while significantly improving overall treatment effectiveness [43].

The application of nanotechnology in medical imaging has revolutionized diagnostic precision by enhancing both sensitivity and specificity across various imaging modalities. Nanoparticle-based imaging agents, including quantum dots and magnetic nanoparticles, serve as highly efficient contrast enhancers that enable clearer visualization of tissues and diseased regions, thereby minimizing false positives and improving overall diagnostic accuracy [11]. Moreover, advancements in nanotechnology have propelled the field of molecular imaging, allowing real-time tracking of cellular and molecular processes. This progress offers deeper insights into disease mechanisms and significantly strengthens the reliability and accuracy of cancer diagnostics [44].

The integration of nanoparticles into cancer treatment has shown remarkable potential, particularly when combined with radiation therapy. Research indicates that nanoparticles can amplify radiation-induced DNA double-strand breaks, leading to enhanced tumor cell destruction and improved survival outcomes in preclinical models findings that support their prospective application in clinical oncology [45]. Moreover, clinical trials across various medical disciplines, especially in cancer therapy, have highlighted the therapeutic versatility of nanoparticles, emphasizing substantial progress in translating nanotechnology from experimental research to practical medicine [46]. Despite these promising developments, the clinical adoption of nanotechnology within radiology continues to face significant challenges. Concerns regarding the safety, biocompatibility, and patient-specific variability of nanomaterials must be carefully addressed to ensure consistent and safe outcomes. Furthermore, while NP-based imaging agents have demonstrated enhanced diagnostic and therapeutic potential, their widespread clinical use remains limited, underscoring the need for continued research and innovation to bridge the gap between laboratory success and real-world medical application [44].

## CHALLENGES, LIMITATIONS, AND SAFETY CONSIDERATIONS

The integration of nanoscale innovations in radiology and imaging within periodontal, implant, and oral medicine presents numerous challenges and limitations. These hurdles include issues related to cytotoxicity, regulatory approval, cost, and the translation of research from bench to clinic. Additionally, ethical considerations, particularly in the context of AI-nano hybrids, further complicate the landscape. Addressing these challenges is crucial for the successful implementation and advancement of these technologies in clinical practice.

Nanomaterials, while offering significant advantages in terms of mechanical strength


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and drug delivery, pose potential risks related to cytotoxicity and long-term biocompatibility. The interaction of nanomaterials with biological tissues can lead to unforeseen toxicological effects, necessitating comprehensive biocompatibility assessments before clinical application [47, 48].

The development of nanomaterial-based dental implants, for instance, requires careful evaluation of their in-vivo performance to ensure they do not induce adverse biological response [48].

The regulatory landscape for nanomedicines is complex and often lacks clear guidelines, which poses a significant barrier to clinical translation. The absence of a well-defined regulatory framework complicates the approval process, as seen with the FDA and EMA, which require extensive clinical trials to ensure safety and efficacy. The need for a globally synchronized regulatory framework is emphasized to facilitate innovation while ensuring patient safety [49].

The high cost of developing and implementing nanoscale technologies in clinical settings is a major limitation. The expense associated with research, development, and regulatory compliance can be prohibitive, potentially limiting access to these advanced treatments [47]. Economic considerations also extend to the cost-effectiveness of these technologies in improving patient outcomes, which must be demonstrated to justify their widespread adoption.

Translating nanoscale innovations from research to clinical practice involves overcoming significant technical and logistical challenges. This includes ensuring the reproducibility and scalability of nanomaterial production, as well as addressing any unforeseen complications that may arise during clinical trials [48, 50]. The integration of AI with nanotechnology in oral health further complicates this process, requiring interdisciplinary collaboration to address technical and ethical challenges [51].

The use of AI-nano hybrids in oral health raises ethical concerns, particularly regarding patient privacy, data security, and informed consent. The potential for biases in AI algorithms and the need for equitable access to these technologies are critical issues that must be addressed. Legal considerations, such as liability in the event of AI-related errors and compliance with data protection laws, are also significant hurdles that require careful navigation [51].

While the potential of nanoscale innovations in periodontal, implant, and oral medicine is immense, these challenges highlight the need for a balanced approach that considers both the benefits and risks. Addressing these hurdles requires collaboration among researchers, clinicians, regulatory bodies, and policymakers to ensure the responsible and sustainable implementation of these technologies. The ethical implications, particularly in the context of AI-nano hybrids, underscore the importance of developing frameworks that prioritize patient safety and equitable access.

## FUTURE DIRECTIONS AND EMERGING TRENDS

The future of nanotechnology in medical imaging and therapy is on the brink of transformative progress, driven by innovations such as hybrid Nano-AI platforms, theranostic systems, genomic-nanoparticle–based personalization, and multimodal imaging technologies. The convergence of AI and nanotechnology is especially promising, leading to the development of intelligent platforms capable of processing complex biomedical datasets for improved diagnostics and individualized treatment planning. By enhancing image analysis, these Nano-AI systems can automate the detection of nanoscale disease markers, enabling earlier diagnosis and more effective monitoring of therapeutic responses. In parallel, nanotheranostic platforms integrate diagnostic and therapeutic functionality within a single system, leveraging materials such as superparamagnetic iron oxide nanoparticles (SPIONs) and gold nanostructures to enhance tumor targeting and controlled drug release through mechanisms like the enhanced permeability and retention effect [52]. These smart systems can be engineered to respond to specific physiological cues such as changes in pH or temperature allowing for real-time tracking and adaptive treatment delivery [53]. Personalized imaging approaches further expand nanomedicine's potential by designing nanoparticles that correspond to an individual's genetic profile, optimizing both imaging accuracy and therapeutic precision, particularly in cancer care where genetic variability plays a critical role [54]. Meanwhile, emerging multimodal imaging techniques that integrate optical coherence tomography (OCT) with nano-contrast agents utilize the unique optical properties of nanomaterials like gold nanoparticles to achieve high-resolution, real-time visualization of biological tissues, thereby





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substantially enhancing diagnostic performance [54, 55]. Despite these significant advances, several obstacles impede clinical translation, including nanoparticle toxicity, manufacturing challenges, and stringent regulatory constraints. Furthermore, ethical considerations and the need for strong interdisciplinary collaboration remain paramount as AI and nanotechnology continue to converge within healthcare systems [52]. With continued research and responsible implementation, these emerging technologies hold tremendous potential to redefine precision oncology and personalized medicine on a global scale.

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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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