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Gold nanoparticles: A powerful biosensor in oral medicine and dentistry

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ABSTRACT

Gold nanoparticles (AuNPs) have emerged as highly effective biosensing agents in oral diagnostics and therapeutic monitoring due to their unique optical, electronic, and surface properties. Their exceptional surface plasmon resonance enables sensitive detection of biomolecules associated with oral diseases, including cancer markers, bacterial antigens, and inflammatory proteins. Functionalized AuNPs can selectively bind to target molecules, allowing for real-time, non-invasive diagnostics through colorimetric assays, fluorescence quenching, and surface-enhanced Raman spectroscopy (SERS). In clinical dentistry, AuNP-based biosensors facilitate early diagnosis of conditions such as periodontal disease, oral squamous cell carcinoma, and peri-implantitis. Their biocompatibility and chemical stability further support integration into smart diagnostic platforms and intraoral devices. As precision dentistry advances, gold nanoparticle biosensors hold promise for transforming point-of-care diagnostics, enabling timely and personalized interventions.

Keywords: Gold nanoparticles, Oral diagnostics, Biosensor technology, Surface plasmon resonance, Nanotechnology.

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Introduction

In therapeutics, AuNPs serve as versatile platforms for targeted drug delivery and antimicrobial therapy. Their ability to penetrate biofilms and release payloads under stimuli like pH or near-infrared light improves treatment efficacy for infections and oral cancers while minimizing side effects (1). Additionally, AuNPs contribute to regenerative dentistry by promoting osteoblast growth and enabling real-time monitoring of bone regeneration around dental implants.

Despite their promise, challenges such as long-term stability, clinical scalability, and regulatory approval remain. Future directions include integrating AuNPs with artificial intelligence for predictive diagnostics and smart dental implants, as well as developing multifunctional, stimuli-responsive systems for personalized care. By bridging nanotechnology with digital health, AuNPs are poised to revolutionize oral healthcare, shifting paradigms from reactive treatments to proactive, precision-based approaches. This review highlights the current applications, advantages, and future potential of AuNPs in transforming dental medicine.

Nanotechnology is a rapidly advancing field that involves the manipulation of matter at the atomic and molecular scale, typically within the range of 1 to 100 nanometers (2). At this scale, materials exhibit unique physical, chemical, and biological properties that differ significantly from their bulk counterparts (3, 4). These novel characteristics enable groundbreaking applications across diverse sectors, including medicine, electronics, energy, and environmental science (5-8). For instance, in medicine (9), nanoparticles are used for targeted drug delivery (10), improving treatment efficacy while minimizing side effects (11-13). In electronics, nanotechnology has led to the development of smaller, faster, and more efficient devices (14). The ability to engineer materials at the nanoscale opens up unprecedented opportunities for innovation, making nanotechnology a cornerstone of modern scientific and technological progress (15).

The interdisciplinary nature of nanotechnology integrates principles from physics, chemistry, biology, and engineering to create functional systems with enhanced performance (16, 17). One of the most promising aspects of nanotechnology is its potential to address global challenges, such as clean energy production, food production, and disease diagnosis (18). For example, nanomaterials like graphene and quantum dots are being explored for their exceptional conductivity and optical properties, which could revolutionize bioimaging and energy storage (19). (20). As research continues to expand, nanotechnology holds the promise of transforming industries and improving quality of life, while also demanding careful consideration of its societal implications (21).

Gold nanoparticles (AuNPs) have emerged as a powerful biosensing tool (22) in oral medicine and dentistry due to their unique optical, electrical, and biocompatible properties (23). Their high surface-to-volume ratio (24) allows for dense functionalization with biomolecules (e.g., antibodies, DNA probes, or enzymes), enhancing their ability to capture and detect disease-specific biomarkers with exceptional sensitivity (25, 26). Additionally, AuNPs exhibit strong surface plasmon resonance (SPR), a phenomenon where incident light interacts with conduction electrons, producing intense, tunable optical signals (27). This property enables colorimetric detection—where the aggregation or dispersion of AuNPs causes visible color shifts—facilitating rapid, instrument-free diagnostics in chairside settings (28).

Beyond optical advantages, AuNPs possess excellent electrical conductivity, making them ideal for electrochemical biosensors that amplify signal transduction when detecting biomarkers in saliva or gingival crevicular fluid (GCF) (28, 29). Their biocompatibility and low toxicity ensure safe integration into oral diagnostic platforms, drug delivery systems, and even dental implants without adverse immune reactions (30-32).

Moreover, AuNPs can be engineered into various shapes (spheres, rods, stars) and sizes (1–100 nm), allowing customization for specific applications, such as photothermal therapy for antibacterial coatings for dental implants (32). Their ease of functionalization with thiolated ligands, polymers, or biomolecules further enhances targeting precision, enabling multiplexed detection of pathogens (e.g., Porphyromonas gingivalis) or inflammatory markers (e.g., IL-6, TNF-α) in a single assay (33-35).

By leveraging these properties, AuNPs are transforming oral healthcare through non-invasive, real-time monitoring of diseases like oral cancer, caries, and periodontitis, while paving the way for personalized, point-of-care dental diagnostics (36, 37).

Gold nanoparticles (AuNPs) have gained significant attention in oral medicine and dentistry due to their remarkable potential in diagnostics, therapeutics, and preventive care (37). Their unique optical, electrical, and biocompatible properties make them ideal for applications ranging from early disease detection to targeted drug delivery (38). In the following sections, we will explore the key applications of AuNPs in oral healthcare, focusing on their role in cancer diagnostics, periodontal disease monitoring, antimicrobial strategies, and regenerative dentistry. By examining these advancements, we can better understand how nanotechnology is shaping the future of dental medicine.

Key Applications of Gold Nanoparticles in Oral Medicine & Dentistry

Early Detection of Oral Diseases

Oral Cancer (Oral Squamous Cell Carcinoma - OSCC)

Gold nanoparticles (AuNPs) have revolutionized the early detection of oral squamous cell carcinoma (OSCC) through their exceptional biosensing capabilities (25). When functionalized with specific antibodies or DNA probes, AuNPs can selectively bind to OSCC biomarkers present in saliva, including interleukin-6 (IL-6), CD44, and matrix metalloproteinase-9 (MMP-9), even at ultralow concentrations (39). This interaction triggers highly sensitive and specific diagnostic signals, enabling non-invasive cancer screening with unprecedented accuracy (40). A key advantage of AuNPs lies in their surface plasmon resonance (SPR) properties, which cause dramatic color shifts when nanoparticle aggregation or dispersion occurs due to biomarker binding (41). In colorimetric assays, this optical phenomenon allows for visual detection of cancer markers without complex instrumentation – a simple color change from red (dispersed AuNPs) to blue/purple (aggregated AuNPs) can indicate the presence of malignant biomarkers (42). This approach has been successfully implemented in lateral flow assays (LFAs) for point-of-care testing, where results can be interpreted using just a saliva sample for the detection of antibodies (43) (Figure 1).

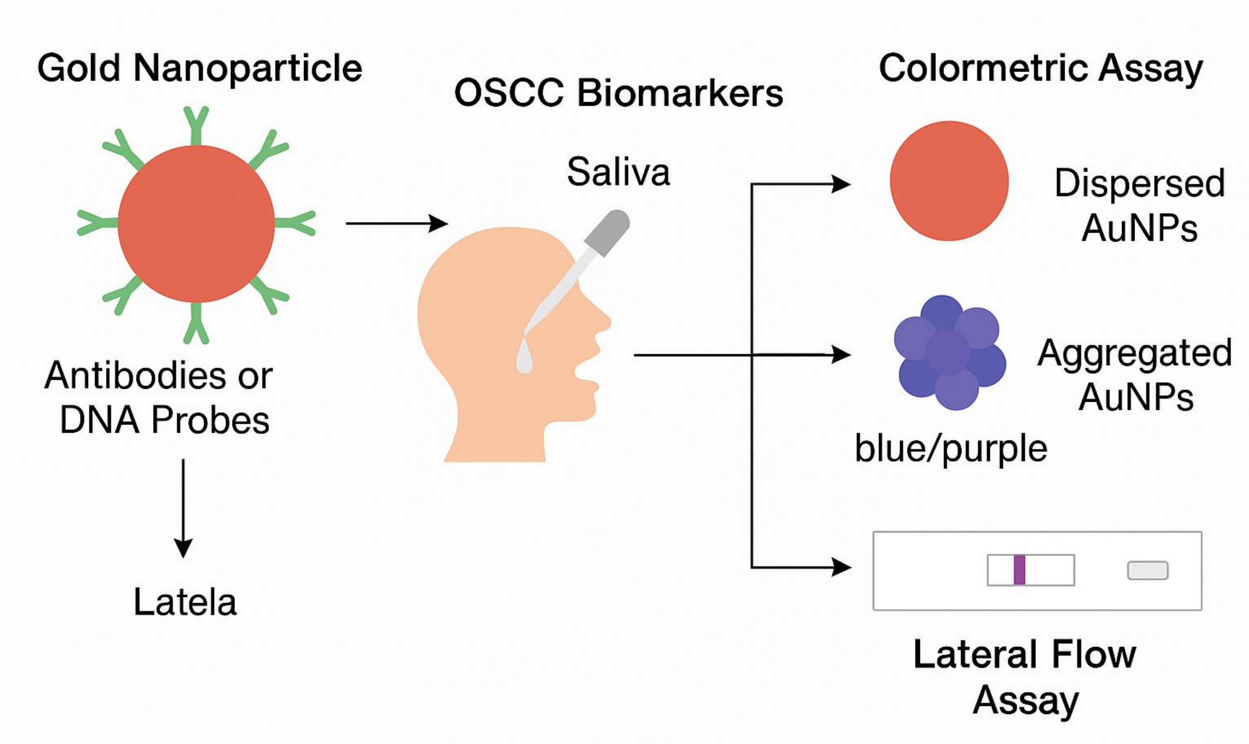

Figure 1. Biosensing Mechanism of Gold Nanoparticles for OSCC Detection

Gold nanoparticle (AuNP)-based diagnostic platforms demonstrate remarkable versatility when integrated with surface-enhanced Raman spectroscopy (SERS), achieving better functionality compared to conventional methods (44). the utilization of gold fluorescence nanoparticles in conjunction with SERS holds tremendous potential for revolutionizing cancer detection (45). The plasmonic properties of AuNPs create electromagnetic "hot spots" that dramatically enhance Raman scattering signals from target molecules (46). Furthermore, AuNP multiplexing capabilities permit simultaneous quantification of multiple distinct cancer biomarkers through spectral fingerprint differentiation, while maintaining rapid assay times (47). Combined with portable SERS reader technology, this multi-analyte detection capacity enables comprehensive oral cancer screening in primary care settings with good sensitivity/specificity, revolutionizing early OSCC detection paradigms (48).

The nanotechnology-driven approaches represent a transformative paradigm shift in oral oncology diagnostics, effectively replacing invasive tissue biopsies with rapid, chairside saliva tests offering suitable diagnostic accuracy in multicenter trials (49, 50). The transition to non-invasive AuNP-based assays demonstrates greater sensitivity than conventional histopathology for early-stage OSCC detection, while eliminating procedural risks and patient discomfort (51). Recent advancements are being validated in longitudinal studies monitoring high-risk populations, linear discriminant analysis (PCA-LDA) and logistic regression (LR), revealing a sensitivity of 89% and 68% and a diagnostic accuracy of 73% and 60% for saliva and oral cells, respectively (52)(Figure 2).

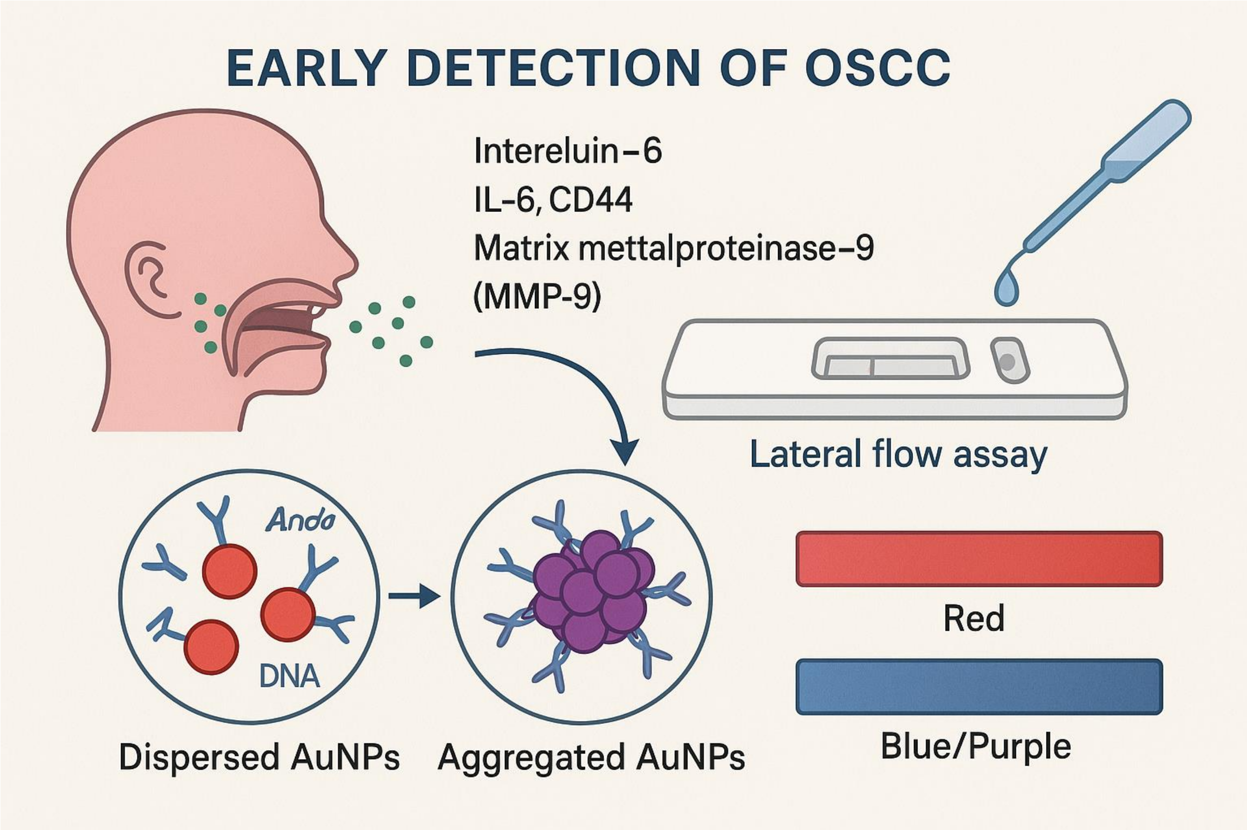

Figure 2. Gold Nanoparticle-Based Lateral Flow Assay for Early OSCC Detection

Periodontal Disease

Gold nanoparticles (AuNPs) enable highly sensitive periodontal pathogen detection through multiple mechanisms. A recent study developed a gold nanoparticle (AuNP)-based biosensor that detects protease activity (e.g., gingipains from Porphyromonas gingivalis) by monitoring localized surface plasmon resonance (LSPR) peak shifts. When proteases like trypsin or gingipains (Kgp/RgpB) degrade the casein coating on AuNPs, a blueshift (~1–2 nm) occurs, while bacterial supernatants cause a redshift (~2 nm) due to nonspecific protein binding. The sensor demonstrated high sensitivity, with a detection limit < 0.1 μg/mL (4.3 nM)—well below gingipain levels in severe periodontitis (~50 μg/mL)—and specificity, as only gingipain-active samples induced significant shifts. This cost-effective, rapid system shows promise for chair-side periodontal diagnostics by enabling real-time detection of pathogenic protease activity (53). Electrochemical biosensors utilize antibody-coated AuNPs immobilized on electrodes to generate quantifiable electrical signals during pathogen binding, with a 2024 study demonstrating high sensitivity for salivary biomarkers detection within 9 minutes (54, 55). Additionally, surface-enhanced Raman spectroscopy (SERS) leverages AuNPs' plasmonic properties to amplify bacterial biomarker signals, permitting multiplexed detection of multiple pathogens in a single assay through their unique spectral fingerprints (56). These complementary approaches provide rapid, sensitive, and quantitative alternatives to conventional periodontal diagnostics.

Gold nanoparticles (AuNPs) revolutionize inflammatory biomarker monitoring in periodontitis by enabling ultrasensitive quantification of key cytokines in gingival crevicular fluid (GCF) (57). For critical markers like IL-10, antibody-conjugated AuNPs in electrochemical sensors achieve remarkable detection limits (as demonstrated by graphene-AuNP hybrid systems) (58).In addition, aptamer-functionalized AuNPs facilitate rapid, colorimetric semi-quantitative assessment of inflammation severity (59). Additionally, MMP-8-specific aptamer-AuNP complexes permit early identification of active periodontal tissue destruction prior to radiographic evidence, and osteocalcin-sensitive AuNP sensors precisely track bone remodeling dynamics during regenerative therapies (60). These AuNP-based platforms collectively provide unprecedented precision in periodontal disease staging, enabling 1- earlier intervention through sensitive cytokine detection, 2- real-time treatment monitoring, and 3- personalized therapeutic approaches through multiplexed biomarker analysis - all with minimal sample requirements and rapid turnaround times ideal for clinical implementation (57).

The next generation of AuNP-based periodontal diagnostics is poised to integrate with emerging technologies through three transformative approaches: 1- Smartphone-compatible AuNP sensors wirelessly transmit pathogen loads and cytokine levels to clinician dashboards via mobile apps, enabling real-time remote monitoring—a strategy first validated in cancer diagnostics (61); 2- AI-powered predictive systems that analyze longitudinal AuNP sensor data through machine learning algorithms to forecast individual disease trajectories and optimize treatment timing (61); and 3- Theranostic AuNP platforms combining simultaneous pathogen detection with on-demand release of antimicrobial peptides or anti-inflammatory drugs directly within periodontal pockets (62). Together, these advancements are fundamentally transforming periodontal disease management by enabling unprecedentedly early, accurate, and non-invasive (saliva/GCF-based) monitoring of both microbial and host factors (63). This technological convergence is catalyzing a paradigm shift from reactive, symptom-driven treatment to truly personalized, preemptive periodontal care, with clinical trials already demonstrating improvement in treatment outcomes through AuNP-guided therapy adjustments. Table 1 summarizes the key applications of gold nanoparticles (AuNPs) in detecting oral diseases, highlighting the targeted biomarkers, detection methods, and advantages over traditional diagnostic approaches (Table 1).

Table 1. Key Applications of AuNPs in Oral Disease Detection

Disease	AuNP-Based Detection Method	Biomarkers/Pathogens	Advantages
Oral Cancer (OSCC)	Colorimetric assays, SERS, lateral flow assays (LFAs).	IL-6, CD44, MMP-9.	Non-invasive, chairside results (89% sensitivity), replaces tissue biopsies.
Periodontitis	LSPR shifts, electrochemical sensors.	Gingipains (P. gingivalis), IL-10, MMP-8.	Detects proteolytic activity at <0.1 µg/mL; real-time monitoring.
Dental Caries	SERS, colorimetric bacterial binding.	S. mutans, Lactobacillus spp., lactic acid.	Multiplexed detection (<10^3 CFU/mL); visual readout.
Peri-Implantitis	AuNP-coated implants, biofilm sensors.	Bacterial biofilms (e.g., P. gingivalis).	Early infect

This table summarizes the major diagnostic applications of AuNPs in various oral diseases, highlighting specific detection methods, target biomarkers or pathogens, and the clinical advantages offered. From non-invasive cancer screening to real-time monitoring of periodontal pathogens, AuNP-based technologies demonstrate high sensitivity, rapid diagnostics, and potential for point-of-care use.

Dental Caries & Bacterial Biofilm Detection and Prevention

Gold nanoparticles (AuNPs) are transforming dental caries and biofilm management through their multifunctional optical, electrochemical, and antimicrobial properties (64). When functionalized with caries-specific antibodies or aptamers, AuNPs enable ultrasensitive (<10^3 CFU/mL) detection of cariogenic pathogens like Streptococcus mutans and Lactobacillus spp. via three synergistic mechanisms: 1-Colorimetric assays using antibody-conjugated AuNPs that exhibit visible red-to-blue transitions upon bacterial binding in saliva, enabling instrument-free chairside diagnosis (65); 2-Electrochemical sensors with AuNP-modified electrodes that quantify bacterial metabolites (e.g., lactic acid) at picomolar concentrations for precise caries risk stratification (66); and 3- Surface-enhanced Raman spectroscopy (SERS) platforms where AuNPs amplify pathogen-specific spectral fingerprints, permitting multiplexed identification of multiple biofilm-associated microorganisms in dental plaque samples (67). This tri-modal detection capability - combining visual, electrical, and spectroscopic readouts - allows for real-time, quantitative assessment of both planktonic bacteria and established biofilms, significantly advancing early caries intervention strategies.

Gold nanoparticles (AuNPs) have emerged as a promising tool for dental caries prevention by leveraging their unique antibacterial, biofilm-disrupting, and remineralization properties (68). Functionalized AuNPs can selectively target cariogenic bacteria like

Streptococcus mutans through surface modifications with antimicrobial peptides or chitosan, disrupting bacterial membranes and inhibiting biofilm formation (69). Near-infrared (NIR) light-activated AuNPs generate localized hyperthermia, effectively eradicating mature biofilms while sparing healthy tissue (70). Additionally, AuNPs enhance remineralization by serving as scaffolds for hydroxyapatite deposition, repairing early enamel lesions (71). Their ability to penetrate biofilms and deliver fluoride or antimicrobial agents directly to caries-prone sites further improves preventive efficacy (72). With biocompatibility and customizable surface chemistry, AuNPs offer a multifaceted approach to caries management, combining antibacterial action, biofilm control, and enamel repair in a single platform.

The future of AuNP-based caries management is evolving toward smart, predictive systems through groundbreaking developments that integrate nanotechnology with artificial intelligence and personalized medicine (73). Researchers are developing multifunctional AuNP platforms capable of real-time biofilm monitoring via wireless sensors, which transmit data to AI algorithms that predict caries risk and optimize treatment timing (74). Additionally, pH-responsive AuNP carriers are being engineered to autonomously release antimicrobials or remineralizing agents only when acidic conditions are detected, enabling targeted therapy with minimal disruption to oral microbiota (75). Furthermore, advances in bioactive AuNP composites for dental materials promise long-term protection by combining sustained antimicrobial activity with enhanced mechanical properties in fillings and sealants (76). These innovations collectively herald a new era of precision dentistry, where AuNP-enabled systems provide continuous, proactive caries prevention tailored to individual patient needs.

Salivary Diagnostics

Saliva is an emerging diagnostic medium that contains a wide array of biomarkers, including proteins, nucleic acids, hormones, and metabolites, which can indicate both oral and systemic diseases such as diabetes, HIV, and human papillomavirus (HPV). Unlike blood-based diagnostics, saliva collection is non-invasive, cost-effective, and easily accessible, making it ideal for point-of-care (POC) testing (77-79). However, detecting low-abundance biomarkers in saliva requires highly sensitive and specific analytical techniques (80). Gold nanoparticles (AuNPs) have gained significant attention in salivary diagnostics due to their unique optical, electrical, and biocompatible properties (36, 81). Their high surface-to-volume ratio allows for efficient biomarker conjugation, while their localized surface plasmon resonance (LSPR) enables colorimetric detection, making them ideal for rapid diagnostic applications (82).

One of the most promising applications of AuNPs in salivary diagnostics is in lateral flow assays (LFAs), which provide a simple, low-cost, and rapid detection method suitable for chairside testing (83). In AuNP-based LFAs, saliva samples are applied to a test strip, where target biomarkers bind to AuNP-conjugated antibodies (84). As the sample migrates via capillary action, the AuNP-analyte complexes are captured at specific test lines, producing a visible color change that indicates the presence of the biomarker (85). This technology has been successfully employed for detecting oral diseases (e.g., periodontal pathogens, oral cancer biomarkers) and systemic conditions (e.g., HIV antibodies, glucose levels for diabetes monitoring) (86-88). The advantages of AuNP-LFAs include minimal sample preparation, rapid results (less than 20 minutes), and no requirement for sophisticated laboratory equipment, making them particularly valuable in resource-limited settings (89).

Recent advancements in AuNP-LFAs have focused on improving sensitivity and multiplexing capabilities. For instance, integrating fluorescent or magnetic labels with AuNPs enhances detection limits, enabling the identification of trace biomarkers in saliva (90, 91). (92). Despite these advantages, challenges remain, such as optimizing saliva sample collection to avoid variability and ensuring long-term stability of AuNP conjugates (93). Future research aims to develop smartphone-compatible LFAs for quantitative analysis, leveraging machine learning for enhanced diagnostic accuracy (94). As AuNP-based salivary diagnostics continue to evolve, they hold immense potential for revolutionizing early disease detection, personalized medicine, and global health monitoring.

Gold nanoparticle (AuNP)-based salivary diagnostics offer several key advantages that make them highly valuable for clinical applications. First, their non-invasive sample collection method is patient-friendly, particularly beneficial for pediatric and geriatric populations who may struggle with blood draws (95). Second, they provide rapid results, typically less than 20 minutes, significantly faster than traditional lab-based assays that can take hours (89). Third, they are cost-effective and portable, making them ideal for low-resource and remote settings where advanced laboratory infrastructure is unavailable (96). Additionally, AuNPs enhance sensitivity and specificity due to their unique plasmonic properties, enabling the detection of low-concentration biomarkers in saliva (96). Finally, these assays have the potential for multiplex detection, allowing simultaneous screening of multiple diseases from a single sample, which improves diagnostic efficiency (97). Together, these advantages position AuNP-based salivary diagnostics as a transformative tool in point-of-care testing and personalized medicine.

Drug Delivery & Antimicrobial Therapy

Gold nanoparticles (AuNPs) are revolutionizing dentistry (98). Their unique properties and biocompatibility make them ideal for targeted therapies (99). AuNPs improve drug delivery in periodontal infections. For example, doxycycline-loaded AuNPs enable precise antibiotic release (100). They also enhance antifungal treatments. Nystatin-conjugated AuNPs effectively combat oral candidiasis (101). In oral cancer, AuNPs enable photothermal therapy (PTT). They absorb near-infrared light, generating localized heat. This heat selectively kills cancer cells while sparing healthy tissue (102).

AuNPs enhance drug stability and tissue penetration. They also allow controlled release, reducing side effects (103). Their potential in dental therapeutics is transformative. Current research focuses on optimizing biocompatibility. Clinical translation for broader applications is underway (104). AuNPs promise safer, more effective dental treatments.

Gold nanoparticles (AuNPs) demonstrate exceptional potential in treating oral infections, particularly periodontal diseases caused by pathogens like *Porphyromonas gingivalis* and *Aggregatibacter actinomycetemcomitans*, where conventional antibiotics often fail due to poor biofilm penetration and systemic side effects (105, 106). Doxycycline-loaded AuNPs (10–100 nm) enhance drug stability, enable sustained release in periodontal pockets, and penetrate subgingival biofilms (107). Surface modifications (e.g., chitosan coatings) improve mucoadhesion for prolonged localized action, reducing toxicity and enhancing biofilm disruption (108, 109). For oral candidiasis, nystatin-loaded AuNPs boost antifungal efficacy by improving solubility and cellular uptake. Targeted delivery via Candida-specific ligands and dual mechanisms—membrane disruption and ROS generation—provides superior activity over conventional treatments (110).

Gold nanoparticles (AuNPs) enable highly effective photothermal therapy (PTT) for oral cancer by leveraging their strong surface plasmon resonance (SPR) to absorb near-infrared (NIR) light (700–1100 nm) and convert it into localized heat, which selectively destroys cancer cells while sparing healthy tissue—this selectivity arises from the enhanced permeability and retention (EPR) effect, allowing preferential accumulation of AuNPs in tumors, where NIR irradiation (e.g., 808 nm laser) induces hyperthermia for precise ablation (111). Furthermore, AuNPs can be co-loaded with chemotherapeutic agents (e.g., cisplatin) to synergize PTT with chemotherapy, enhancing tumor suppression while overcoming drug resistance through heat-mediated sensitization (112). Compared to conventional therapies, PTT with AuNPs offers a minimally invasive approach with superior precision, especially when functionalized with targeting ligands (e.g., anti-EGFR antibodies), reducing off-target effects and improving treatment outcomes for oral cancer (113).

Looking ahead, gold nanoparticles (AuNPs) hold immense potential for multifunctional applications in dentistry, combining antimicrobial, anti-inflammatory, and regenerative properties, especially for comprehensive periodontal therapy, though challenges remain in clinical translation, requiring standardized toxicity studies and regulatory approvals to ensure safety and efficacy (114-117). The development of smart, stimuli-responsive AuNPs (e.g., pH- or enzyme-triggered drug release) could further enhance precision in treating infections and oral cancers (118, 119). As a versatile platform, AuNPs revolutionize dental therapeutics by enabling targeted drug delivery for periodontal and fungal infections while offering precision cancer treatment through photothermal therapy, with their ability to boost drug efficacy, minimize side effects, and integrate with advanced therapies marking a paradigm shift in dental care—future research must now focus on optimizing biocompatibility and clinical applicability to unlock their full potential for widespread use (120, 121).

Dental Implant & Bone Regeneration Monitoring

Gold nanoparticles (AuNPs) are transforming dental implantology through their unique optical and bioactive properties (122). In peri-implantitis detection, AuNP-coated implants sense bacterial biofilms, enabling early intervention. In addition, they were demonstrated to be effective in inactivating the bacteria attached to the implant surface (123).AuNP-enhanced scaffolds promote osteoblast growth for bone regeneration, which can be widely applicable for use in bone tissue

regenerative therapy, both in orthopedic and dental settings (124). These smart systems offer early infection alerts, controlled drug release, and improved bone integration, outperforming conventional approaches (123, 125, 126). Future challenges include optimizing long-term stability and clinical scalability, but AuNPs promise to make dental implants more durable and responsive.

Titanium (Ti) dental implants, while biocompatible, often face challenges like bacterial infection and peri-implantitis due to their lack of inherent antibacterial activity (127). To address this, researchers have explored surface modifications using antimicrobial agents, including reactive oxygen species (ROS)-based therapies like photodynamic therapy (PDT) and sonodynamic therapy (SDT) (128, 129). Among these, SDT stands out due to ultrasound's deep tissue penetration and precision (130). (131). Unlike silver nanoparticles, AuNPs offer superior biocompatibility and stability, making them ideal for long-term antibacterial applications. Recent studies demonstrate that AuNP-decorated TiO_2 nanotubes (AuNPs-TNTs) significantly improve antibacterial performance against pathogens like P. gingivalis, a key contributor to peri-implant infections (123). By combining AuNPs' plasmonic effects with ultrasound's deep-penetrating capability, this nanoplatform provides a safe, efficient, and minimally invasive solution for preventing biofilm-related implant failures, offering a novel approach to combat peri-implantitis and enhance dental implant success (123).

Gold nanoparticles (AuNPs) significantly enhance bone regeneration scaffolds by improving both structural and functional properties (132): AuNPs can promote the osteogenic differentiation of periodontal ligament stem cell sheets by upregulating bone-related protein expression and mineralization (133). Besides being used as a carrier for stable delivery of biologically active molecules, GNPs are an intriguing substance for use in bone tissue engineering, given their inherent enhancement of bone regeneration (134). Additionally, AuNPs facilitate real-time monitoring of bone formation - colorimetric detection of alkaline phosphatase (ALP) via visible gold nanoparticle aggregation (135). These multifunctional capabilities provide three major advantages over conventional scaffolds: 1- continuous feedback on healing progress, 2- on-demand drug delivery to prevent complications, and 3- enhanced mechanical strength without sacrificing biocompatibility, ultimately leading to more predictable and successful bone regeneration around dental implants (136-138).

Gold nanoparticles (AuNPs) could transform next-generation dental implants. These smart systems combine infection detection, drug release, and bone regeneration monitoring (32, 125, 139). AI-powered diagnostics could analyze AuNP sensor data for predictive care (140). However, challenges remain. AuNP coatings must stay stable in the harsh oral environment in the long term. Standardized biosensing protocols are needed for clinical adoption. Cost-effective manufacturing must also be achieved for widespread use. Overcoming these hurdles will require focused research. Scalable fabrication methods and rigorous clinical validation are key. Success could revolutionize oral healthcare. Implants would shift from passive structures to intelligent therapeutic systems. These advanced implants would enable early disease detection and personalized treatment. They could also monitor healing in real time. This would improve implant longevity and patient outcomes while reducing complications.

Advantages of AuNP-Based Biosensors in Dentistry

Gold nanoparticle (AuNP)-based biosensors are transforming dental diagnostics through their unparalleled sensitivity (detecting biomarkers at picomolar concentrations), enabled by precise functionalization with antibodies or aptamers for targeted pathogen identification (e.g., P. gingivalis, C. albicans), while offering rapid, non-invasive chairside testing via saliva or GCF analysis with colorimetric/electrochemical results in minutes (141-143). Their multiplex capability allows simultaneous detection of diverse biomarkers (bacteria, cytokines, pH), providing comprehensive oral health assessments, all within a biocompatible platform that outperforms other nanomaterials in safety and integrates seamlessly with digital dentistry tools like smartphone readers and AI analytics for real-time treatment monitoring (144, 145). These advancements enable early disease intervention before radiographic changes occur, facilitate personalized treatment plans, and reduce healthcare costs by minimizing complex lab tests.

Future Perspectives: The Next Frontier of AuNPs in Dentistry

Gold nanoparticles (AuNPs) are set to revolutionize dentistry by merging nanotechnology with digital health solutions, enabling three transformative advancements: 1- AI-integrated AuNP sensors for real-time disease monitoring through wearable oral devices (e.g., smart mouthguards) that track salivary biomarkers, with machine learning predicting disease progression and enabling telehealth integration (146); 2- smart dental implants with embedded AuNP sensors smart implants and wearable sensors, enable real-time monitoring of implant stability, healing progress, and patient-specific factors, allowing for timely interventions if needed (147); and 3- personalized point-of-care (POC) devices, including disposable AuNP strips for rapid pathogen detection and smartphone-connected biosensors for at-home testing, allowing tailored treatments based on real-time microbial profiles (148, 149). Together, these innovations promise to shift dentistry toward proactive, data-driven, and precision-based care. Table 2 summarizes the clinical advantages and current challenges of AuNP-based technologies in dentistry, highlighting their transformative potential alongside key hurdles for widespread adoption (table.2).

Table 2. Clinical Advantages and Challenges of AuNP-Based Technologies in Dentistry

Aspect	Advantages	Challenges
Diagnostics	Non-invasive (saliva/GCF samples), rapid results (<20 minutes), high sensitivity (picomolar detection).	Variability in saliva collection; long-term stability of AuNP conjugates.
Therapeutics	Targeted drug delivery (e.g., doxycycline for periodontitis), reduced side effects.	Optimizing drug-loading efficiency; scaling up production for clinical use.
Preventive Care	Antibacterial coatings for implants: biofilm disruption via photothermal therapy.	Cost-effective fabrication; regulatory approval for nanomaterials.
Bone Regeneration	AuNP-enhanced scaffolds promote osteoblast growth and real-time healing monitoring.	Ensuring long-term stability of AuNP coatings in harsh oral environments.
Future Integration	AI-powered predictive analytics; smart implants with real-time monitoring.	Standardizing protocols; addressing ethical and saftey

This table outlines the multifaceted roles of AuNPs in diagnostics, therapeutics, preventive care, bone regeneration, and future smart technologies. While AuNPs offer significant benefits such as non-invasive diagnostics, targeted treatments, and enhanced tissue regeneration, challenges remain in areas like material stability, regulatory hurdles, and ethical integration of emerging technologies.

Conclusion

Gold nanoparticles (AuNPs) are revolutionizing modern dentistry by enabling breakthroughs in oral diagnostics, therapeutics, and preventive care through their unique ability to facilitate ultra-sensitive, rapid, and non-invasive disease detection while serving as versatile platforms for targeted drug delivery and smart dental materials. By integrating AuNPs into advanced biosensors, antimicrobial therapies, and responsive implant coatings, dental professionals can now achieve unprecedented precision in diagnosing conditions like peri-implantitis and oral cancer at early stages, delivering site-specific treatments with minimal side effects, and monitoring treatment efficacy in real-time - ultimately transforming conventional dental practice into a more predictive, preventive, and personalized approach to oral healthcare.

Declaration of Interest

The authors of this article declared no conflict of interest.

Ethical Considerations

Not applicable.

Authors' Contributions

All authors equally contributed to this study.

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Transparency of Data

In accordance with the principles of transparency and open research, we declare that all data and materials used in this study are available upon request.

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Declaration

In order to correct and improve the academic writing of our paper, we have used the language model ChatGPT.

References

1. Mousavi SM, Hashemi SA, Mazraedoost S, Chiang W-H, Yousefi K, Arjmand O, et al. Anticancer, antimicrobial and biomedical features of polyoxometalate as advanced materials: A review study. Inorganic Chemistry Communications. 2022;146:110074.
2. Dowling AP. Development of nanotechnologies. Materials today. 2004;7(12):30-5.
3. Joudeh N, Linke D. Nanoparticle classification, physicochemical properties, characterization, and applications: a comprehensive review for biologists. Journal of Nanobiotechnology. 2022;20(1):262.
4. Eskandari F, Abbaszadegan A, Gholami A, Ghahramani Y. The antimicrobial efficacy of graphene oxide, double antibiotic paste, and their combination against Enterococcus faecalis in the root canal treatment. BMC Oral Health. 2023;23(1):20.
5. Biswas P, Wu C-Y. Nanoparticles and the environment. Journal of the air & waste management association. 2005;55(6):708-46.
6. Zhang L, Gu F, Chan J, Wang A, Langer R, Farokhzad O. Nanoparticles in medicine: therapeutic applications and developments. Clinical pharmacology & therapeutics. 2008;83(5):761-9.
7. Matsui I. Nanoparticles for electronic device applications: a brief review. Journal of chemical engineering of Japan. 2005;38(8):535-46.
8. Baxter J, Bian Z, Chen G, Danielson D, Dresselhaus MS, Fedorov AG, et al. Nanoscale design to enable the revolution in renewable energy. Energy & Environmental Science. 2009;2(6):559-88.
9. Ghahramani Y, Yaghoobi F, Motamedi R, Jamshidzadeh A, Abbaszadegan A. Effect of Endodontic Irrigants and Medicaments Mixed with Silver Nanoparticles against Biofilm Formation of Enterococcus faecalis. Iran Endod J. 2018;13(4):559-64. Epub 2018/10/01. doi: 10.22037/iej.v13i4.21843. PubMed PMID: 36883019; PubMed Central PMCID: PMC9985693.
10. Nabavizadeh M, Ghahramani Y, Abbaszadegan A, Jamshidzadeh A, Jenabi P, Makarempour A. In vivo biocompatibility of an ionic liquid-protected silver nanoparticle solution as root canal irrigant. Iranian endodontic journal. 2018;13(3):293.
11. De Jong WH, Borm PJ. Drug delivery and nanoparticles: applications and hazards. International journal of nanomedicine. 2008;3(2):133-49.
12. Mousavi SM, Nezhad FF, Ghahramani Y, Binazadeh M, Javidi Z, Azhdari R, et al. Recent Advances in Bioactive Carbon Nanotubes Based on Polymer Composites for Biosensor Applications. Chem Biodivers. 2024;21(7):e202301288. Epub 2024/05/03. doi: 10.1002/cbdv.202301288. PubMed PMID: 38697942.
13. Adl A, Abbaszadegan A, Gholami A, Parvizi F, Ghahramani Y. Effect of a New Imidazolium-based Silver Nanoparticle Irrigant on the Bond Strength of Epoxy Resin Sealer to Root Canal Dentine. Iran Endod J. 2019;14(2):122-5. Epub 2019/04/01. doi: 10.22037/iej.v14i2.22589. PubMed PMID: 36855446; PubMed Central PMCID: PMC9968383.
14. Payal, Pandey P. Role of nanotechnology in electronics: A review of recent developments and patents. Recent patents on nanotechnology. 2022;16(1):45-66.
15. Moazami F, Gholami A, Mehrabi V, Ghahramani Y. Evaluation of the Antibacterial and Antifungal Effects of ProRoot MTA and Nano-fast Cement: An In Vitro Study. J Contemp Dent Pract. 2020;21(7):760-4. Epub 2020/10/07. PubMed PMID: 33020359.
16. Porter AL, Youtie J. How interdisciplinary is nanotechnology? Journal of nanoparticle research. 2009;11:1023-41.
17. Nabavizadeh MR, Moazzami F, Gholami A, Mehrabi V, Ghahramani Y. Cytotoxic Effect of Nano Fast Cement and ProRoot Mineral Trioxide Aggregate on L-929 Fibroblast Cells: an in vitro Study. J Dent (Shiraz). 2022;23(1):13-9. Epub 2022/03/17. doi: 10.30476/dentjods.2021.87208.1239. PubMed PMID: 35291684; PubMed Central PMCID: PMC8918640.
18. Pokrajac L, Abbas A, Chrzanowski W, Dias GM, Eggleton BJ, Maguire S, et al. Nanotechnology for a sustainable future: Addressing global challenges with the international network4sustainable nanotechnology. ACS Publications; 2021.
19. Kumar YR, Deshmukh K, Sadasivuni KK, Pasha SK. Graphene quantum dot based materials for sensing, bio-imaging and energy storage applications: a review. RSC advances. 2020;10(40):23861-98.
20. Isibor PO. Regulations and policy considerations for nanoparticle safety. Environmental Nanotoxicology: Combatting the Minute Contaminants: Springer; 2024. p. 295-316.
21. Tawiah B, Ofori EA, George SC. Nanotechnology in societal development. Nanotechnology in Societal Development: Springer; 2024. p. 1-64.
22. Mousavi SM, Hashemi SA, Fallahi Nezhad F, Binazadeh M, Dehdashtijahromi M, Omidifar N, et al. Innovative Metal-Organic Frameworks for Targeted Oral Cancer Therapy: A Review. Materials (Basel). 2023;16(13). Epub 2023/07/14. doi: 10.3390/ma16134685. PubMed PMID: 37444999; PubMed Central PMCID: PMC10342828.
23. Li Y, Schluesener HJ, Xu S. Gold nanoparticle-based biosensors. Gold Bulletin. 2010;43(1):29-41.

24. Abbaszadegan A, Ghahramani Y, Farshad M, Sedigh-Shams M, Gholami A, Jamshidzadeh A. In Vitro Evaluation of Dynamic Viscosity, Surface Tension and Dentin Wettability of Silver Nanoparticles as an Irrigation Solution. Iran Endod J. 2019;14(1):23-7. Epub 2019/01/01. doi: 10.22037/iej.v14i1.21758. PubMed PMID: 36879595; PubMed Central PMCID: PMC9984811.
25. Saha K, Agasti SS, Kim C, Li X, Rotello VM. Gold Nanoparticles in Chemical and Biological Sensing. Chemical Reviews. 2012;112(5):2739-79. doi: 10.1021/cr2001178.
26. Giljohann DA, Seferos DS, Daniel WL, Massich MD, Patel PC, Mirkin CA. Gold nanoparticles for biology and medicine. Spherical nucleic acids. 2020:55-90.
27. Jain PK, Lee KS, El-Sayed IH, El-Sayed MA. Calculated Absorption and Scattering Properties of Gold Nanoparticles of Different Size, Shape, and Composition: Applications in Biological Imaging and Biomedicine. The Journal of Physical Chemistry B. 2006;110(14):7238-48. doi: 10.1021/jp057170o.
28. Rosi NL, Mirkin CA. Nanostructures in Biodiagnostics. Chemical Reviews. 2005;105(4):1547-62. doi: 10.1021/cr030067f.
29. Chen A, Chatterjee S. Nanomaterials based electrochemical sensors for biomedical applications. Chemical Society Reviews. 2013;42(12):5425-38.
30. Alkilany AM, Murphy CJ. Toxicity and cellular uptake of gold nanoparticles: what we have learned so far? Journal of nanoparticle research. 2010;12:2313-33.
31. Dreaden EC, Alkilany AM, Huang X, Murphy CJ, El-Sayed MA. The golden age: gold nanoparticles for biomedicine. Chemical Society Reviews. 2012;41(7):2740-79.
32. Zhan X, Yan J, Tang H, Xia D, Lin H. Antibacterial properties of gold nanoparticles in the modification of medical implants: a systematic review. Pharmaceutics. 2022;14(12):2654.
33. Svärd A, Neilands J, Palm E, Svensäter G, Bengtsson Tr, Aili D. Protein-functionalized gold nanoparticles as refractometric nanoplasmonic sensors for the detection of proteolytic activity of porphyromonas gingivalis. ACS Applied Nano Materials. 2020;3(10):9822-30.
34. de la Rica R, Stevens MM. Plasmonic ELISA for the ultrasensitive detection of disease biomarkers with the naked eye. Nature Nanotechnology. 2012;7(12):821-4. doi: 10.1038/nnano.2012.186.
35. Lévy R, Thanh NTK, Doty RC, Hussain I, Nichols RJ, Schiffrin DJ, et al. Rational and Combinatorial Design of Peptide Capping Ligands for Gold Nanoparticles. Journal of the American Chemical Society. 2004;126(32):10076-84. doi: 10.1021/ja0487269.
36. Zhang Q, Hou D, Wen X, Xin M, Li Z, Wu L, et al. Gold nanomaterials for oral cancer diagnosis and therapy: Advances, challenges, and prospects. Materials Today Bio. 2022;15:100333. doi: https://doi.org/10.1016/j.mtbio.2022.100333.
37. Bapat RA, Chaubal TV, Dharmadhikari S, Abdulla AM, Bapat P, Alexander A, et al. Recent advances of gold nanoparticles as biomaterial in dentistry. International journal of pharmaceutics. 2020;586:119596.
38. Kumar A, Zhang X, Liang X-J. Gold nanoparticles: emerging paradigm for targeted drug delivery system. Biotechnology advances. 2013;31(5):593-606.
39. Balapure A, Goel S, Dubey SK, Javed A, Chattopadhyay S. A review: early detection of oral cancer biomarkers using microfluidic colorimetric point-of-care devices. Analytical Methods. 2024.
40. Tai J, Fan S, Ding S, Ren L. Gold nanoparticles based optical biosensors for cancer biomarker proteins: a review of the current practices. Frontiers in bioengineering and biotechnology. 2022;10:877193.
41. El-Sayed IH, Huang X, El-Sayed MA. Surface Plasmon Resonance Scattering and Absorption of anti-EGFR Antibody Conjugated Gold Nanoparticles in Cancer Diagnostics: Applications in Oral Cancer. Nano Letters. 2005;5(5):829-34. doi: 10.1021/nl050074e.
42. Mirkin CA, Letsinger RL, Mucic RC, Storhoff JJ. A DNA-based method for rationally assembling nanoparticles into macroscopic materials. Nature. 1996;382(6592):607-9. doi: 10.1038/382607a0.
43. Di Nardo F, Cavalera S, Baggiani C, Giovannoli C, Anfossi L. Direct vs Mediated Coupling of Antibodies to Gold Nanoparticles: The Case of Salivary Cortisol Detection by Lateral Flow Immunoassay. ACS Applied Materials & Interfaces. 2019;11(36):32758-68. doi: 10.1021/acsami.9b11559.
44. Indrasekara ASD, Paladini BJ, Naczynski DJ, Starovoytov V, Moghe PV, Fabris L. Dimeric Gold Nanoparticle Assemblies as Tags for SERS-Based Cancer Detection. Advanced healthcare materials. 2013;2(10):1370-6.
45. Kalashgrani MY, Mousavi SM, Akmal MH, Gholami A, Omidifar N, Chiang WH, et al. Gold fluorescence nanoparticles for enhanced SERS detection in biomedical sensor applications: current trends and future directions. The Chemical Record. 2024:e202300303.
46. Hang Y, Wang A, Wu N. Plasmonic silver and gold nanoparticles: shape-and structure-modulated plasmonic functionality for point-of-caring sensing, bio-imaging and medical therapy. Chemical Society Reviews. 2024;53(6):2932-71.
47. Choi N, Dang H, Das A, Sim MS, Chung IY, Choo J. SERS biosensors for ultrasensitive detection of multiple biomarkers expressed in cancer cells. Biosensors and Bioelectronics. 2020;164:112326.
48. Kah JCY, Wei KK, Leng LCG, James RC, Sheppard, Xiang SZ, et al. Early diagnosis of oral cancer based on the surface plasmon resonance of gold nanoparticles. International Journal of Nanomedicine. 2007;2(4):785-98. doi: 10.2147/IJN.S2.4.785.
49. Onishi T, Mihara K, Matsuda S, Sakamoto S, Kuwahata A, Sekino M, et al. Application of magnetic nanoparticles for rapid detection and in situ diagnosis in clinical oncology. Cancers. 2022;14(2):364.
50. Chen Y, Sun B, Marcella C. Evaluation of the diagnostic accuracy of superparamagnetic iron oxide nanoparticles on breast cancer: a systematic review and meta-analysis. International Journal of Scientific Research in Dental and Medical Sciences. 2023;5(1):27-34.
51. Viswambari Devi R, Doble M, Verma RS. Nanomaterials for early detection of cancer biomarker with special emphasis on gold nanoparticles in immunoassays/sensors. Biosensors and Bioelectronics. 2015;68:688-98. doi: https://doi.org/10.1016/j.bios.2015.01.066.
52. Connolly JM, Davies K, Kazakeviciute A, Wheatley AM, Dockery P, Keogh I, et al. Non-invasive and label-free detection of oral squamous cell carcinoma using saliva surface-enhanced Raman spectroscopy and multivariate analysis. Nanomedicine: Nanotechnology, Biology and Medicine. 2016;12(6):1593-601. doi: https://doi.org/10.1016/j.nano.2016.02.021.
53. Svärd A, Neilands J, Palm E, Svensäter G, Bengtsson T, Aili D. Protein-Functionalized Gold Nanoparticles as Refractometric Nanoplasmonic Sensors for the Detection of Proteolytic Activity of Porphyromonas gingivalis. ACS Applied Nano Materials. 2020;3(10):9822-30. doi: 10.1021/acsanm.0c01899.
54. Cesewski E, Johnson BN. Electrochemical biosensors for pathogen detection. Biosensors and Bioelectronics. 2020;159:112214. doi: https://doi.org/10.1016/j.bios.2020.112214.

55. Verma S, Singh A, Shukla A, Kaswan J, Arora K, Ramirez-Vick J, et al. Anti-IL8/AuNPs-rGO/ITO as an immunosensing platform for noninvasive electrochemical detection of oral cancer. ACS applied materials & interfaces. 2017;9(33):27462-74.
56. Berry ME, Kearns H, Graham D, Faulds K. Surface enhanced Raman scattering for the multiplexed detection of pathogenic microorganisms: towards point-of-use applications. Analyst. 2021;146(20):6084-101.
57. Zhang Q, Wang Z, Shen S, Wang J, Cao J, Deng Y, et al. Integrating enzyme-nanoparticles bring new prospects for the diagnosis and treatment of immune dysregulation in periodontitis. Frontiers in Cellular and Infection Microbiology. 2024;Volume 14 - 2024. doi: 10.3389/fcimb.2024.1494651.
58. Baek SH, Song HW, Lee S, Kim J-E, Kim YH, Wi J-S, et al. Gold Nanoparticle-Enhanced and Roll-to-Roll Nanoimprinted LSPR Platform for Detecting Interleukin-10. Frontiers in Chemistry. 2020;Volume 8 - 2020. doi: 10.3389/fchem.2020.00285.
59. Karami P, Afsar T, Gholamin D, Pahlavan Y, Johari-Ahar M. Nanoparticles-based biosensor devices developed for point-of-care (POC) analyses of c-reactive protein (CRP) as the clinically important inflammatory biomarker. Chemical Papers. 2025;79(2):615-35.
60. Tortolini C, Gigli V, Angeloni A, Tasca F, Thanh NTK, Antiochia R. A disposable immunosensor for the detection of salivary MMP-8 as biomarker of periodontitis. Bioelectrochemistry. 2024;156:108590. doi: https://doi.org/10.1016/j.bioelechem.2023.108590.
61. Khoshfetrat SM, Seyed Dorraji P, Shayan M, Khatami F, Omidfar K. Smartphone-based electrochemiluminescence for visual simultaneous detection of RASSF1A and SLC5A8 tumor suppressor gene methylation in thyroid cancer patient plasma. Analytical chemistry. 2022;94(22):8005-13.
62. D'Amico E, Aceto GM, Petrini M, Cinquini C, D'Ercole S, Iezzi G, et al. How Will Nanomedicine Revolutionize Future Dentistry and Periodontal Therapy? International Journal of Molecular Sciences. 2025;26(2):592. PubMed PMID: doi:10.3390/ijms26020592.
63. Aminu N, Chan S-Y, Toh S-M. Roles of nanotechnological approaches in periodontal disease therapy. Journal of Applied Pharmaceutical Science. 2017;7(7):234-42.
64. Zhu T, Huang Z, Shu X, Zhang C, Dong Z, Peng Q. Functional nanomaterials and their potentials in antibacterial treatment of dental caries. Colloids and Surfaces B: Biointerfaces. 2022;218:112761.
65. Yang J, Wang X, Sun Y, Chen B, Hu F, Guo C, et al. Recent advances in colorimetric sensors based on gold nanoparticles for pathogen detection. Biosensors. 2022;13(1):29.
66. Webster MS, Cooper JS, Chow E, Hubble LJ, Sosa-Pintos A, Wieczorek L, et al. Detection of bacterial metabolites for the discrimination of bacteria utilizing gold nanoparticle chemiresistor sensors. Sensors and Actuators B: Chemical. 2015;220:895-902.
67. Ivleva NP, Wagner M, Horn H, Niessner R, Haisch C. Raman microscopy and surface-enhanced Raman scattering (SERS) for in situ analysis of biofilms. Journal of biophotonics. 2010;3(8-9):548-56.
68. Kamath KA, Nasim I, Rajeshkumar S. Evaluation of the re-mineralization capacity of a gold nanoparticle-based dental varnish: An: in vitro: study. Journal of Conservative Dentistry. 2020;23(4):390-4.
69. Su C, Huang K, Li H-H, Lu Y-G, Zheng D-L. Antibacterial properties of functionalized gold nanoparticles and their application in oral biology. Journal of Nanomaterials. 2020;2020(1):5616379.
70. Han Q, Lau JW, Do TC, Zhang Z, Xing B. Near-Infrared Light Brightens Bacterial Disinfection: Recent Progress and Perspectives. ACS Applied Bio Materials. 2021;4(5):3937-61. doi: 10.1021/acsabm.0c01341.
71. Chen X, Liu H, Zhang Q, Chen X, Wang L, Yu Y, et al. Carboxymethyl chitosan stabilized AuNPs/ACP nanohybrids in enamel white spot lesions. Frontiers in Bioengineering and Biotechnology. 2024;12:1421887.
72. Joshi AS, Singh P, Mijakovic I. Interactions of Gold and Silver Nanoparticles with Bacterial Biofilms: Molecular Interactions behind Inhibition and Resistance. International Journal of Molecular Sciences. 2020;21(20):7658. PubMed PMID: doi:10.3390/ijms21207658.
73. Askari VR, Moradpour A, Alizadeh O, Fadaei MS, Fadaei MR. Biosensors in dentistry. Applications of Biosensors in Healthcare: Elsevier; 2025. p. 399-416.
74. Ray RR, Pattnaik S. Technological advancements for the management of oral biofilm. Biocatalysis and Agricultural Biotechnology. 2024;56:103017. doi: https://doi.org/10.1016/j.bcab.2023.103017.
75. He Y, Vasilev K, Zilm P. pH-Responsive Biomaterials for the Treatment of Dental Caries—A Focussed and Critical Review. Pharmaceutics. 2023;15(7):1837. PubMed PMID: doi:10.3390/pharmaceutics15071837.
76. Amruth B, Somashekarappa H, Maurya M, Nandaprakash M, Somashekar R. Molecular dynamic studies of gold nanoparticles in a dental material TEGDMA. Journal of Molecular Modeling. 2025;31(1):27.
77. Arunkumar S, Arunkumar J, Krishna N, Shakunthala G. Developments in diagnostic applications of saliva in oral and systemic diseases-A comprehensive review. J Sci Innov Res. 2014;3(3):372-87.
78. Viswanath B, Choi CS, Lee K, Kim S. Recent trends in the development of diagnostic tools for diabetes mellitus using patient saliva. TrAC Trends in Analytical Chemistry. 2017;89:60-7.
79. Turner DO, Williams-Cocks SJ, Bullen R, Catmull J, Falk J, Martin D, et al. High-risk human papillomavirus (HPV) screening and detection in healthy patient saliva samples: a pilot study. BMC oral health. 2011;11:1-8.
80. Li Y, Ou Y, Fan K, Liu G. Salivary diagnostics: Opportunities and challenges. Theranostics. 2024;14(18):6969.
81. Chakraborty D, Viveka TS, Arvind K, Shyamsundar V, Kanchan M, Alex SA, et al. A facile gold nanoparticle–based ELISA system for detection of osteopontin in saliva: Towards oral cancer diagnostics. Clinica Chimica Acta. 2018;477:166-72.
82. Jazayeri MH, Aghaie T, Nedaeinia R, Manian M, Nickho H. Rapid noninvasive detection of bladder cancer using survivin antibody-conjugated gold nanoparticles (GNPs) based on localized surface plasmon resonance (LSPR). Cancer Immunology, Immunotherapy. 2020;69:1833-40.
83. Maher S, Kamel M, Demerdash Z, El Baz H, Sayyouh O, Saad A, et al. Gold conjugated nanobodies in a signal-enhanced lateral flow test strip for rapid detection of SARS-CoV-2 S1 antigen in saliva samples. Scientific Reports. 2023;13(1):10643.
84. Lei R, Wang D, Arain H, Mohan C. Design of gold nanoparticle vertical flow assays for point-of-care testing. Diagnostics. 2022;12(5):1107.
85. Minaee S, Sohrabi MR, Mortazavinik S. Rapid and naked-eye colorimetric detection of ultra trace sumatriptan in drinking water, saliva, and human urine samples based on the aggregation of gold nanoparticles. Spectrochimica Acta Part A: Molecular and Biomolecular Spectroscopy. 2023;302:123039.
86. He W, You M, Li Z, Cao L, Xu F, Li F, et al. Upconversion nanoparticles-based lateral flow immunoassay for

point-of-care diagnosis of periodontitis. Sensors and Actuators B: Chemical. 2021;334:129673.

87. Chen X, Du C, Zhao Q, Zhao Q, Wan Y, He J, et al. Rapid and visual identification of HIV-1 using reverse transcription loop-mediated isothermal amplification integrated with a gold nanoparticle-based lateral flow assay platform. Frontiers in Microbiology. 2023;14:1230533.

88. Ang SH, Yu CY, Ang GY, Chan YY, binti Alias Y, Khor SM. A colloidal gold-based lateral flow immunoassay for direct determination of haemoglobin A1c in whole blood. Analytical Methods. 2015;7(9):3972-80.

89. Cho I-H, Bhunia A, Irudayaraj J. Rapid pathogen detection by lateral-flow immunochromatographic assay with gold nanoparticle-assisted enzyme signal amplification. International Journal of Food Microbiology. 2015;206:60-6. doi: https://doi.org/10.1016/j.ijfoodmicro.2015.04.032.

90. Kang KA, Wang J, Jasinski JB, Achilefu S. Fluorescence manipulation by gold nanoparticles: from complete quenching to extensive enhancement. Journal of nanobiotechnology. 2011;9:1-13.

91. Saha A, Ben Halima H, Saini A, Gallardo-Gonzalez J, Zine N, Viñas C, et al. Magnetic Nanoparticles Fishing for Biomarkers in Artificial Saliva. Molecules. 2020;25(17):3968. PubMed PMID: doi:10.3390/molecules25173968.

92. Huang L, Tian S, Zhao W, Liu K, Ma X, Guo J. Multiplexed detection of biomarkers in lateral-flow immunoassays. Analyst. 2020;145(8):2828-40.

93. Li Y, Ou Y, Fan K, Liu G. Salivary diagnostics: opportunities and challenges. Theranostics. 2024;14(18):6969-90. Epub 20241021. doi: 10.7150/thno.100600. PubMed PMID: 39629130; PubMed Central PMCID: PMC11610148.

94. Park J. Smartphone based lateral flow immunoassay quantifications. Journal of Immunological Methods. 2024;533:113745. doi: https://doi.org/10.1016/j.jim.2024.113745.

95. Shang L-J, Yu S-Q, Shang X-W, Wei X-Y, Wang H-Y, Jiang W-S, et al. A non-invasive glucose sensor based on 3D reduced graphene oxide-MXene and AuNPs composite electrode for the detection of saliva glucose. Journal of Applied Electrochemistry. 2024;54(8):1807-17.

96. Eftekhari A, Hasanzadeh M, Sharifi S, Dizaj SM, Khalilov R, Ahmadian E. Bioassay of saliva proteins: The best alternative for conventional methods in non-invasive diagnosis of cancer. International Journal of Biological Macromolecules. 2019;124:1246-55. doi: https://doi.org/10.1016/j.ijbiomac.2018.11.277.

97. Pomili T, Donati P, Pompa PP. Based multiplexed colorimetric device for the simultaneous detection of salivary biomarkers. Biosensors. 2021;11(11):443.

98. Jongrungsomran S, Pissuwan D, Yavirach A, Rungsiyakull C, Rungsiyakull P. The integration of gold nanoparticles into dental biomaterials as a novel approach for clinical advancement: A narrative review. Journal of Functional Biomaterials. 2024;15(10):291.

99. Kadhim RJ, Karsh EH, Taqi ZJ, Jabir MS. Biocompatibility of gold nanoparticles: In-vitro and In-vivo study. Materials Today: Proceedings. 2021;42:3041-5.

100. Kumaar NR, and Nair SC. Nanomaterials: an intra-periodontal Pocket drug-delivery System for Periodontitis. Therapeutic Delivery. 2023;14(3):227-49. doi: 10.4155/tde-2023-0001.

101. Anwar A, Siddiqui R, Shah M, Khan N. Gold nanoparticles conjugation enhances antiacanthamoebic properties of nystatin, fluconazole and amphotericin B. 2019.

102. Liu Z, Shi J, Zhu B, Xu Q. Development of a multifunctional gold nanoplatform for combined chemo-photothermal therapy against oral cancer. Nanomedicine. 2020;15(7):661-76.

103. Voliani V, Signore G, Nifosi R, Ricci F, Luin S, Beltram F. Smart delivery and controlled drug release with gold nanoparticles: new frontiers in nanomedicine. Recent Patents on Nanomedicine. 2012;2(1):34-44.

104. Dykman L, Khlebtsov N. Gold nanoparticles in biomedical applications: recent advances and perspectives. Chemical Society Reviews. 2012;41(6):2256-82.

105. Allaker RP, Memarzadeh K. Nanoparticles and the control of oral infections. International journal of antimicrobial agents. 2014;43(2):95-104.

106. Zhang M, Liu X, Xie Y, Zhang Q, Zhang W, Jiang X, et al. Biological safe gold nanoparticle-modified dental aligner prevents the Porphyromonas gingivalis biofilm formation. ACS omega. 2020;5(30):18685-92.

107. Haddada MB, Jeannot K, Spadavecchia J. Novel Synthesis and Characterization of Doxycycline-Loaded Gold Nanoparticles: The Golden Doxycycline for Antibacterial Applications. Particle & Particle Systems Characterization. 2019;36(2):1800395.

108. Huq MA, Ashrafudoulla M, Parvez MAK, Balusamy SR, Rahman MM, Kim JH, et al. Chitosan-coated polymeric silver and gold nanoparticles: biosynthesis, characterization and potential antibacterial applications: a review. Polymers. 2022;14(23):5302.

109. Calvo NL, Sreekumar S, Svetaz LA, Lamas MC, Moerschbacher BM, Leonardi D. Design and characterization of chitosan nanoformulations for the delivery of antifungal agents. International journal of molecular sciences. 2019;20(15):3686.

110. Sousa F, Ferreira D, Reis S, Costa P. Current Insights on Antifungal Therapy: Novel Nanotechnology Approaches for Drug Delivery Systems and New Drugs from Natural Sources. Pharmaceuticals. 2020;13(9):248. PubMed PMID: doi:10.3390/ph13090248.

111. Azzopardi EA, Ferguson EL, Thomas DW. The enhanced permeability retention effect: a new paradigm for drug targeting in infection. Journal of Antimicrobial Chemotherapy. 2013;68(2):257-74.

112. Comenge J, Sotelo C, Romero F, Gallego O, Barnadas A, Parada TG-C, et al. Detoxifying antitumoral drugs via nanoconjugation: the case of gold nanoparticles and cisplatin. 2012.

113. Riley RS, Day ES. Gold nanoparticle-mediated photothermal therapy: applications and opportunities for multimodal cancer treatment. Wiley Interdisciplinary Reviews: Nanomedicine and Nanobiotechnology. 2017;9(4):e1449.

114. Song W, Ge S. Application of antimicrobial nanoparticles in dentistry. Molecules. 2019;24(6):1033.

115. Dharman S, Kumar R, Shanmugasundaram K. Synthesis and characterisation of novel turmeric gold nanoparticles and evaluation of its anti-oxidant, anti-inflammatory, antibacterial activity for application in oral mucositis-An in vitro study. Int J Dentistry Oral Sci. 2021;8(05):2525-32.

116. Pecci-Lloret MP, Gea-Alcocer S, Murcia-Flores L, Rodríguez-Lozano FJ, Oñate-Sánchez RE. Use of nanoparticles in Regenerative Dentistry: a systematic review. Biomimetics. 2024;9(4):243.

117. Niżnik Ł, Noga M, Kobylarz D, Frydrych A, Krośniak A, Kapka-Skrzypczak L, et al. Gold Nanoparticles (AuNPs)—Toxicity, Safety and Green Synthesis: A Critical Review. International Journal of Molecular Sciences. 2024;25(7):4057. PubMed PMID: doi:10.3390/ijms25074057.

118. Nam J, Won N, Jin H, Chung H, Kim S. pH-induced aggregation of gold nanoparticles for photothermal cancer therapy. Journal of the American Chemical Society. 2009;131(38):13639-45.

119. Amina SJ, Guo B. A review on the synthesis and functionalization of gold nanoparticles as a drug delivery vehicle. International journal of nanomedicine. 2020:9823-57.
120. Roy A. Targeted drug delivery systems used in dentistry-A short review. Drug Invention Today. 2018;10.
121. Yang W, Liang H, Ma S, Wang D, Huang J. Gold nanoparticle based photothermal therapy: Development and application for effective cancer treatment. Sustainable Materials and Technologies. 2019;22:e00109.
122. Gupta A, Singh S. Multimodal potentials of gold nanoparticles for bone tissue engineering and regenerative medicine: avenues and prospects. Small. 2022;18(29):2201462.
123. Sun Y, Xu W, Jiang C, Zhou T, Wang Q. Gold nanoparticle decoration potentiate the antibacterial enhancement of TiO2 nanotubes via sonodynamic therapy against peri-implant infections. Frontiers in Bioengineering and Biotechnology. 2022;10:1074083.
124. Lee SJ, Lee H-J, Kim S-Y, Seok JM, Lee JH, Kim WD, et al. In situ gold nanoparticle growth on polydopamine-coated 3D-printed scaffolds improves osteogenic differentiation for bone tissue engineering applications: in vitro and in vivo studies. Nanoscale. 2018;10(33):15447-53.
125. Guerrero AR, Hassan N, Escobar CA, Albericio F, Kogan MJ, Araya E. Gold nanoparticles for photothermally controlled drug release. Nanomedicine. 2014;9(13):2023-39.
126. Heo DN, Ko W-K, Lee HR, Lee SJ, Lee D, Um SH, et al. Titanium dental implants surface-immobilized with gold nanoparticles as osteoinductive agents for rapid osseointegration. Journal of colloid and interface science. 2016;469:129-37.
127. Liu H, Carter P, Laan A, Eelkema R, Denkova A. Singlet Oxygen Sensor Green is not a suitable probe for 1O2 in the presence of ionizing radiation, Sci. Rep. 9 (2019) 1–8.
128. Xu J, Liu N, Wu D, Gao Z, Song Y-Y, Schmuki P. Upconversion nanoparticle-assisted payload delivery from TiO2 under near-infrared light irradiation for bacterial inactivation. ACS nano. 2019;14(1):337-46.
129. Xu T, Zhao S, Lin C, Zheng X, Lan M. Recent advances in nanomaterials for sonodynamic therapy. Nano Research. 2020;13:2898-908.
130. Zhu W, Chen Q, Jin Q, Chao Y, Sun L, Han X, et al. Sonodynamic therapy with immune modulatable two-dimensional coordination nanosheets for enhanced anti-tumor immunotherapy. Nano Research. 2021;14:212-21.
131. Jie H, Park H, Chae K-H, Anpo M, Park J-K. Suppressed recombination of electrons and holes and its role on the improvement of photoreactivity of flame-synthesized TiO2 nanopowders. Chemical Physics Letters. 2009;470(4-6):269-74.
132. Samadian H, Khastar H, Ehterami A, Salehi M. Bioengineered 3D nanocomposite based on gold nanoparticles and gelatin nanofibers for bone regeneration: In vitro and in vivo study. Scientific reports. 2021;11(1):13877.
133. Zhang Y, Wang P, Wang Y, Li J, Qiao D, Chen R, et al. Gold nanoparticles promote the bone regeneration of periodontal ligament stem cell sheets through activation of autophagy. International journal of nanomedicine. 2021:61-73.
134. Li H, Pan S, Xia P, Chang Y, Fu C, Kong W, et al. Advances in the application of gold nanoparticles in bone tissue engineering. Journal of biological engineering. 2020;14:1-15.
135. Li CM, Zhen SJ, Wang J, Li YF, Huang CZ. A gold nanoparticles-based colorimetric assay for alkaline phosphatase detection with tunable dynamic range. Biosensors and Bioelectronics. 2013;43:366-71. doi: https://doi.org/10.1016/j.bios.2012.12.015.
136. Tiwari PM, Vig K, Dennis VA, Singh SR. Functionalized gold nanoparticles and their biomedical applications. Nanomaterials. 2011;1(1):31-63.
137. Li H, Pan S, Xia P, Chang Y, Fu C, Kong W, et al. Advances in the application of gold nanoparticles in bone tissue engineering. Journal of Biological Engineering. 2020;14(1):14. doi: 10.1186/s13036-020-00236-3.
138. Yadid M, Feiner R, Dvir T. Gold nanoparticle-integrated scaffolds for tissue engineering and regenerative medicine. Nano letters. 2019;19(4):2198-206.
139. Heo DN, Ko W-K, Bae MS, Lee JB, Lee D-W, Byun W, et al. Enhanced bone regeneration with a gold nanoparticle–hydrogel complex. Journal of Materials Chemistry B. 2014;2(11):1584-93.
140. Moore JA, Chow JCL. Recent progress and applications of gold nanotechnology in medical biophysics using artificial intelligence and mathematical modeling. Nano Express. 2021;2(2):022001. doi: 10.1088/2632-959X/abddd3.
141. Liu X, Dai Q, Austin L, Coutts J, Knowles G, Zou J, et al. A one-step homogeneous immunoassay for cancer biomarker detection using gold nanoparticle probes coupled with dynamic light scattering. Journal of the American Chemical Society. 2008;130(9):2780-2.
142. Hegde M, Pai P, Shetty MG, Babitha KS. Gold nanoparticle based biosensors for rapid pathogen detection: A review. Environmental Nanotechnology, Monitoring & Management. 2022;18:100756.
143. António M, Lima T, Vitorino R, Daniel-da-Silva AL. Interaction of colloidal gold nanoparticles with urine and saliva biofluids: An exploratory study. Nanomaterials. 2022;12(24):4434.
144. Wang L, O 'Donoghue MB, Tan W. Nanoparticles for multiplex diagnostics and imaging. Nanomedicine. 2006;1(4):413-26.
145. Kaur B, Kaur K, editors. Using Artificial Intelligence and Mathematical Modeling for Advancement of Gold Nanotechnology in Therapeutic Biophysics. 2021 2nd Global Conference for Advancement in Technology (GCAT); 2021: IEEE.
146. Arya SS, Dias SB, Jelinek HF, Hadjileontiadis LJ, Pappa A-M. The convergence of traditional and digital biomarkers through AI-assisted biosensing: A new era in translational diagnostics? Biosensors and Bioelectronics. 2023;235:115387.
147. Panahi O, Panahi U. AI-Powered IoT: Transforming Diagnostics and Treatment Planning in Oral Implantology. J Adv Artif Intell Mach Learn. 2025;1(1):1-4.
148. Xu X, Wu X, Kuang H, Song S. Gold nanoparticle-based lateral flow strips for rapid and sensitive detection of Virginiamycin M1. Food and Agricultural Immunology. 2020;31(1):764-77.
149. Timpel J, Klinghammer S, Riemenschneider L, Ibarlucea B, Cuniberti G, Hannig C, et al. Sensors for in situ monitoring of oral and dental health parameters in saliva. Clinical Oral Investigations. 2023;27(10):5719-36.