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Emerging Applications Of Nanotechnology In Orthodontics: A Review

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Abstract
Nanotechnology has emerged as a transformative force in modern orthodontics, offering innovative solutions to longstanding clinical challenges such as plaque accumulation, enamel demineralization, prolonged treatment duration, and appliance failure. Manipulating materials at the nanoscale, orthodontic components—including wires, brackets, adhesives, ligatures, power chains, and temporary anchorage devices—have been enhanced for superior antimicrobial activity, mechanical strength, biocompatibility, and surface durability. Incorporation of nanoparticles like silver, zinc oxide, titanium dioxide, and bioactive glass has shown promising results in reducing white spot lesions, improving bracket bonding, and resisting bacterial colonization. Surface modification techniques like nanoimprinting and nanocoating have further optimized the functional and hygienic properties of orthodontic materials. However, despite these advantages, challenges such as cytotoxicity, lack of long-term clinical data, regulatory barriers, and high production costs remain. This review consolidates current evidence on the applications, benefits, and limitations of nanotechnology in orthodontics, emphasizing its potential to enhance treatment outcomes and patient care while highlighting the need for further clinical validation.

INTRODUCTION

According to the Greek, "nano" means "dwarf." Nanotechnology is the science of altering matter, measured in billionths of meters or nanometers, which is around the size of two or three atoms. What mainly distinguishes it is its action at a scale of one billionth of a meter, or one ten thousandth of the breadth of a human hair. In short, it's molecular or atomic engineering [1]. According to the Romans, who displayed an early example of nanotechnology in the form of the Lycurgus Cup, which is currently housed in the collection of the British Museum, the use of nanoparticles and nanostructures dates back to the fourth century AD [2].Significant progress has been made in the field of orthodontics in recent decades, especially in the creation of materials meant to enhance patient comfort, treatment effectiveness, and aesthetics. Of them, nanotechnology has shown itself to be a transformational and promising strategy. Nanotechnology, which is defined as the manipulation of matter at the nanoscale scale (1–100 nm), has made it possible to create new materials that have better mechanical, chemical, and biological qualities than their traditional equivalents. Nanotechnology has great promise for addressing a number of clinical issues in orthodontics, including wire corrosion, plaque buildup, enamel decalcification, and extended treatment times.

Nanoparticles, particularly silver, zinc oxide, and titanium dioxide, have been shown to increase antibacterial activity, bond strength, and reduce friction when added to orthodontic adhesives, wires, and brackets. By compiling recent studies and demonstrating the potential of nanotechnology to improve modern orthodontic practice, this study seeks to be a vital resource for academicians, researchers, and clinicians. By compiling recent studies and demonstrating the potential of nanotechnology to improve modern orthodontic practice, this study seeks to be a vital resource for academicians, researchers, and clinicians.

Applications of Nanotechnology in Orthodontics

1. Antibacterial activity

Plaque builds up around bands and brackets as a result of fixed orthodontic appliances. There are impacts of fixed orthodontic appliances on subgingival microbiota and periodontal state because the microbial makeup of tooth plaque is intimately linked to the health of periodontal tissue [4]. (Fig. 1). The buildup of cariogenic biofilm on the enamel/adhesive interface is one of the primary causes of enamel demineralization during orthodontic treatment with fixed appliances. Researchers are looking for novel alternative approaches as a result of the significant rise in antibiotic-resistant strains and the antimicrobial drugs' weak points, such as their high toxicity and short-term antimicrobial activity. Therefore, silver nanoparticles are essential for preventing bacterial growth in both solid and aqueous environments because of their strong reactivity, which is a result of their large surface-to-volume ratio [5].A reaction against the denaturation effects of silver ions causes the bacterial DNA molecules to condense and lose their capacity to replicate. Additionally, thiol groups in proteins interact with silver ions, causing the bacterial proteins to become inactive. [7]

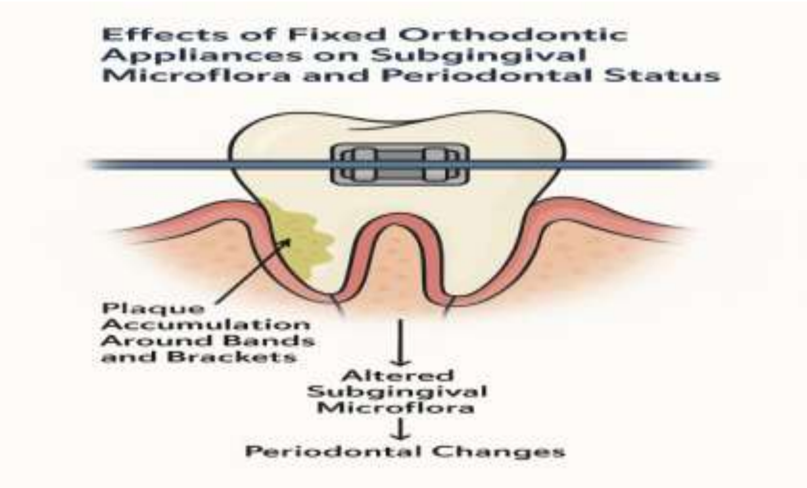

Figure 1.

2. Nanocoatings in Archwires and Brackets

Types of Nanocoatings

a. Titanium Dioxide (TiO_2) Nanocoating

TiO_2 is widely used due to its photocatalytic and antibacterial properties. Studies show that TiO_2-coated brackets reduce bacterial colonization, especially *Streptococcus mutans*, and also improve corrosion resistance [8,9].

b. Silver Nanoparticles (AgNPs)

Silver has well-known antimicrobial activity. Coating brackets or wires with AgNPs significantly reduces bacterial growth and may prevent white spot lesions during orthodontic treatment [10]. However, concerns regarding cytotoxicity necessitate dose control.

c. Zinc Oxide (ZnO) Nanocoatings

ZnO exhibits both antibacterial and anti-inflammatory effects. ZnO nanoparticle coatings on stainless steel wires reduce friction and inhibit microbial growth [11].

d. Fluorinated Nanocoatings

Fluoride-containing nanocoatings provide remineralization benefits while offering antibacterial effects. They are promising in reducing demineralization adjacent to brackets [12].

e. Carbon-Based Nanomaterials

Graphene oxide and carbon nanotubes have been explored for their superior mechanical strength, thermal conductivity, and antimicrobial effects. Graphene coatings improve surface hardness and reduce microbial adhesion [13].

Benefits of Nanocoated Orthodontic Components

a. Reduced Friction: Nanocoated archwires, especially with TiO_2 or ZnO, demonstrate reduced frictional resistance, enabling more efficient tooth movement [14].

b. Corrosion Resistance: The protective nanolayer acts as a barrier against corrosion, especially in acidic or fluoride-rich environments [15].

c. Antibacterial Properties: Coatings with AgNPs, TiO_2, and ZnO significantly inhibit bacterial colonization, reducing the risk of gingival inflammation and white spot lesions [16].

d. Improved Biocompatibility: Surface modifications at the nanoscale enhance the interaction between the material and oral tissues, promoting better biocompatibility [17].

3. Nanoparticles in Orthodontic Dental Adhesives

Nanoparticles have been incorporated into orthodontic adhesives to improve their antimicrobial efficacy, mechanical performance, and longevity of bracket bonding. Their inclusion addresses critical issues such as biofilm formation, white spot lesions (WSLs), and bond failure under masticatory forces. This review outlines the various types of nanoparticles used in orthodontic adhesives, their clinical relevance, and current limitations[18]

Types of Nanoparticles Used in Orthodontic Adhesives

a.Silver Nanoparticles (AgNPs)

- Strong broad-spectrum antibacterial agent.
- Prevents Streptococcus mutans and Lactobacillus proliferation around brackets.
- Clinical studies show reduced incidence of WSLs without significant compromise to shear bond strength (SBS) at low concentrations [19,20].

b.Zinc Oxide Nanoparticles (ZnO NPs)

- Exhibits antibacterial and antifungal activity.
- ZnO-modified adhesives show sustained antimicrobial action and slight reinforcement in mechanical properties [21].

c.Titanium Dioxide Nanoparticles (TiO_2 NPs)

- Possesses photocatalytic antimicrobial action.
- Improves hardness, durability, and SBS [22].

d.Chitosan Nanoparticles

- Natural, biocompatible, and antimicrobial.
- Reduces bacterial adhesion and supports remineralization [23].

e.Bioactive Glass Nanoparticles

- Releases calcium and phosphate ions, enhancing remineralization.
- Can prevent demineralization around brackets [18].

4. Nanoparticle Delivery from Elastomeric Ligatures

Elastomeric ligatures play a passive role in orthodontic tooth movement but an active one in biofilm accumulation. Their surface texture and inability to release protective agents make them ideal for bacterial adhesion. To counter this, researchers have developed nanoparticle-loaded elastomeric ligatures that continuously release antibacterial or therapeutic agents during orthodontic treatment[24]. Nanoparticles are incorporated into the elastomeric matrix during manufacturing or surface modification. Upon intraoral placement, saliva, temperature, and mechanical stress initiate a slow release of the active agent.

Types of Nanoparticles Used

a. Silver Nanoparticles (AgNPs)

- Most studied; provide long-lasting antibacterial action.
- Effective against *Streptococcus mutans* and *Lactobacillus* species.
- Incorporated ligatures reduce bacterial growth without cytotoxicity [25].

b.Zinc Oxide Nanoparticles (ZnO NPs)

- Antimicrobial and anti-inflammatory.
- ZnO-loaded ligatures show prolonged antimicrobial action and maintain elasticity [26].

c. Titanium Dioxide (TiO_2 NPs)

- Photocatalytic properties enable light-activated antibacterial function.
- TiO_2-coated ligatures reduce plaque adhesion in UV-exposed zones [27].

d.Chitosan Nanoparticles

- Natural polymer with antimicrobial and biocompatible properties.
- Chitosan-elastomer combinations reduce biofilm while being eco-friendly [28].

Clinical Advantages

1. **White Spot Lesion Prevention:** Sustained antimicrobial release reduces early enamel demineralization.
2. **Reduction in Plaque Accumulation:** Lower bacterial adhesion on ligature surfaces improves oral hygiene during orthodontics.
3. **Non-Invasive Drug Delivery:** Ligatures act as passive vehicles without requiring additional compliance from the patient.
4. **Minimally Altered Mechanics:** Proper formulation ensures that the mechanical properties (e.g., elasticity and color stability) remain intact.

5. Nanoimprinting of Power Chains

Orthodontic power chains are elastic modules designed to deliver sustained forces between brackets. Their surface characteristics—porosity, hydrophobicity, and elasticity—can harbor microbial biofilms. Nanoimprinting offers a technique to modify surface topography at the nanoscale, thereby reducing bacterial colonization and improving hygiene around orthodontic appliances without compromising force delivery[29]

Benefits of Nanoimprinted Power Chains

1. Antibacterial Properties

Nanoimprinted patterns can mimic natural bacteriophobic surfaces (e.g., shark skin or lotus leaves), reducing *Streptococcus mutans* and *Lactobacillus* adhesion [29].

2. Improved Oral Hygiene

Smoother or engineered topographies lead to reduced biofilm formation, aiding in the prevention of white spot lesions.

3. Biocompatibility

Modified chains show lower cytotoxicity and better interaction with gingival tissues [30].

4. Durability and Aesthetics

Properly designed nanoimprinted surfaces resist staining and wear, preserving aesthetics throughout treatment duration.

6. Nanocoated Orthodontic Mini-Screws/ Temporary Anchorage Devices (TADs)

TADs are miniaturized titanium screws placed temporarily in alveolar bone to provide skeletal anchorage. Although widely used, early failure rates (10–30%) are still observed, often due to poor primary stability, microbial colonization, or soft-tissue inflammation. Nanocoatings provide an innovative solution by improving both biocompatibility and bioactivity at the bone–implant interface[31]

Types of Nanocoatings Applied to TADs

a. Titanium Dioxide Nanotube (TiO_2-NT) Coatings

- Created via anodization on titanium surfaces.
- Enhance osteoblast adhesion and differentiation.
- Provide a favorable surface for osseointegration without compromising removability [32].

b.Hydroxyapatite (HA) Nanocoating

- Mimics natural bone mineral.
- Improves bone–implant contact, especially in low-density bone.
- Ideal for mini-screws in posterior maxilla or thin cortical bone areas [31].

c. Silver Nanoparticles (AgNPs)

- Antibacterial and antifungal.
- Coating mini-screws with AgNPs reduces microbial colonization and peri-implantitis [33].
- Caution: Overuse may lead to cytotoxicity.

d. Zinc Oxide Nanoparticles (ZnO NPs)

- Antibacterial properties with low toxicity
- Provide sustained ion release and surface protection [34].

e. Biopolymer-Based Nanocoatings (e.g., Chitosan)

- Improve soft-tissue integration and reduce inflammation.
- Serve as a vehicle for drug or antimicrobial delivery [35].

Clinical Implications

Nanocoated TADs can be especially beneficial in:

- Patients with thin cortical bone
- Areas of poor bone quality (e.g., posterior maxilla)
- Long-term anchorage requirements
- Patients with higher caries or periodontal risk

conclusion

Nanotechnology is revolutionizing orthodontics by enhancing material performance, reducing microbial colonization, and improving patient outcomes. Applications such as nanocoated wires, brackets, adhesives, ligatures, power chains, and TADs have demonstrated significant antibacterial, mechanical, and biocompatible advantages. While early research is promising, long-term clinical studies and standardization are needed before widespread implementation. Nonetheless, nanotechnology holds immense potential to elevate orthodontic care into a more efficient, hygienic, and patient-friendly domain.

Limitations of Nanotechnology in Orthodontics

Despite its promising applications, nanotechnology in orthodontics faces several limitations:

1. Cytotoxicity Concerns

Some nanoparticles, especially silver and metal oxides, may exhibit cytotoxic effects at higher concentrations, potentially harming oral tissues and systemic health.

2. Long-Term Safety and Biocompatibility

Limited data is available on the long-term effects of nanoparticle exposure in the oral cavity, especially in pediatric and adolescent patients.

3. Lack of Clinical Standardization

There is no universally accepted protocol for the type, concentration, or method of nanoparticle incorporation, making reproducibility and comparison across studies difficult.

4. Cost and Manufacturing Challenges

The production of nanomaterials often requires advanced technology and strict control, leading to higher costs and limiting accessibility in routine practice.

5. Mechanical Property Alterations

While nanoparticles may improve some properties, they can also negatively affect material elasticity, strength, or aesthetics if not optimized.

6. Regulatory Hurdles

Nanotechnology-based products must pass rigorous regulatory approvals, and many currently lack FDA or CE clearance for clinical orthodontic use.

7. Environmental and Ethical Concerns

Disposal of nanoparticle-containing materials may raise environmental safety issues, and long-term nanoparticle exposure may pose unidentified ecological or biological risks.

REFERENCES

1. Roy P, Roy P. Current Trends of Nanotechnology in Orthodontics. Cureus. 2024 Sep 9;16(9).
2. Liu F, Deng W. Role of Nanoparticles in Restorative Dentistry. Dent Oral Health J. 2024;12(1):45–58.
3. Nanoparticles in Dentistry: A Review Dr. A. Vinita Mary,Int. J. Pharm. Sci. Rev. Res., ISSN: 0976 – 044X, 85(1) – January 2025; Article No. 18, Pages: 111-115
4. Ristic M, Svabic MV, Sasic M, Zelic O. Effects of fixed orthodontic appliances on subgingival microflora. International journal of dental hygiene. 2008 May;6(2):129-36.
5. Lkhagvajav N, Koizhaiganova M, Yasa I, Çelik E, Sari Ö. Characterization and antimicrobial performance of nano silver coatings on leather materials. Braz J Microbiol. 2015;46(1):41–48. doi: 10.1590/S1517-838220130446.
6. Degrazia FW, Leitune VC, Garcia IM, Arthur RA, Samuel SM, Collares FM. Effect of silver nanoparticles on the physicochemical and antimicrobial properties of an orthodontic adhesive. Journal of Applied Oral Science. 2016;24(4):404-10.
7. Feng QL, Wu J, Chen GQ, Cui FZ, Kim TN, Kim JO. A mechanistic study of the antibacterial effect of silver ions on Escherichia coli and Staphylococcus aureus. J Biomed Mater Res. 2000;52(4):662–66

8. Amini F, et al. The effect of TiO_2 coating on bacterial adhesion to orthodontic brackets: An in vitro study. *Dental Press J Orthod.* 2015;20(3):45-50.
9. Kachoei M, et al. Titanium dioxide as a coating material for reducing friction in orthodontics. *Angle Orthod.* 2013;83(4):718-721.
10. Besinis A, et al. The antibacterial effects of silver nanoparticles in orthodontics. *Nanotoxicology*. 2012;6(7):771–782.
11. Ryu JH, et al. Anti-bacterial effect of ZnO nanoparticles coated bracket on orthodontic wires. *Clin Orthod Res.* 2011;15(1):34–39.
12. Kishore G, et al. Evaluation of antibacterial activity of fluoride releasing nano-coating on orthodontic brackets. *J Clin Diagn Res.* 2016;10(4):ZC09-ZC13.
13. Chatterjee S, et al. Graphene oxide as a novel material for reducing microbial adhesion on orthodontic brackets. *J Mater Sci Mater Med.* 2018;29(3):28.
14. Gupta N, et al. Reduction in friction by nanocoated orthodontic archwires. *Am J Orthod Dentofacial Orthop.* 2012;141(5):556-562.
15. Batra P, et al. Corrosion resistance of orthodontic wires with nanocoating. *J Orthod Res.* 2017;5(1):19–24.
16. Hammad SM, et al. Nanoparticle-based coating for inhibiting bacterial adhesion in orthodontics. *Dent Mater J.* 2011;30(1):13–19.
17. López-Valverde N, et al. Nanocoatings and their biocompatibility in orthodontic appliances: a review. *J Clin Exp Dent.* 2021;13(7):e671-e678.
18. Melo MA, Cheng L, Zhang K, Weir MD, Rodrigues LK, Xu HH. Novel dental adhesives containing nanoparticles of silver and amorphous calcium phosphate. *Dent Mater*. 2013;29(2):199–210.
19. Poosti M, Ramazanzadeh B, Zebarjad SM, Javadzadeh P, Naderinasab M, Shakeri MT. Comparison of antibacterial effects of orthodontic composites containing different nanoparticles against Streptococcus mutans. *J Dent (Tehran).* 2013;10(4):329–335.
20. Sodagar A, Bahador A, Khalil S, Saffar Shahroudi A, Sadeghi MA. Effect of silver nano particles on shear bond strength and antibacterial activity of orthodontic adhesive. *Dent Res J (Isfahan).* 2016;13(5):339–345.
21. Ginjupalli K, Shankar YU, Basavarajappa S, Sam G, Malaiappan S. Evaluation of antibacterial activity and bond strength of orthodontic adhesives containing zinc oxide nanoparticles – An in vitro study. *J Orthod Sci.* 2019;8:5.
22. Ebrahim E, Ghazvini K, Shirkhani B, Fallah Tafti A. Evaluation of antibacterial activity and shear bond strength of orthodontic adhesive containing titanium dioxide nanoparticles. *J Dent (Shiraz).* 2020;21(4):263–270.
23. Ahn SJ, Lee SJ, Kook JK, Lim BS. Experimental antimicrobial orthodontic adhesives using nanofillers and silver nanoparticles. *Dent Mater.* 2009;25(2):206–213.
24. Ryu JH, Kwon JS, Kim JH, Choi EH, Kim KM, Lee JY. Antibacterial effect of zinc oxide nanoparticle-coated elastomeric ligatures in orthodontic patients. *Angle Orthod*. 2018;88(4):486–491.
25. Ramakrishnaiah R, Nair AK, Taju S, Banu F, Mathew S. Silver nanoparticle incorporation into orthodontic elastomeric ligatures: Evaluation of antimicrobial properties. *J Orthod Res.* 2018;6(3):123–127.
26. Ryu JH, Kwon JS, Kim JH, Choi EH, Kim KM, Lee JY. Antibacterial effect of zinc oxide nanoparticle-coated elastomeric ligatures in orthodontic patients. *Angle Orthod.* 2018;88(4):486–491.
27. Sun L, Li Y, Jiang X, Guan Z, Du Z. Antibacterial effect of titanium dioxide nanotubes with UV-irradiation against periodontopathic pathogens. *Int J Nanomedicine.* 2015;10:1425–1434.
28. Shalish M, Heling I, Sela MN. Antibacterial properties of chitosan-containing elastomeric ligatures. *Am J Orthod Dentofacial Orthop.* 2010;138(3):317–322.
29. Hasan J, Crawford RJ, Ivanova EP. Antibacterial surfaces: the quest for a new generation of biomaterials. *Trends Biotechnol.* 2013;31(5):295–304.
30. Yamaguchi M, Kasai K, Takada K, Ogata K. Effect of surface modifications of orthodontic elastomeric modules on microbial adhesion. *Angle Orthod.* 2004;74(4):490–494.
31. Kim YJ, Choi JY, Lee JJ, Kim KH, Ku Y, Rhyu IC, et al. The effect of nano-hydroxyapatite coating on the osseointegration of orthodontic mini-implants. *Biomaterials*. 2010;31(13):3304–3310.
32. Zhao L, Mei S, Chu PK, Zhang Y, Wu Z. The influence of hierarchical hybrid micro/nano-textured titanium surface with titania nanotubes on osteoblast functions. *Biomaterials*. 2010;31(19):5072–5082.
33. Yeo IS, Kim HS, Yang J. Biomechanical and histological evaluation of titanium implants coated with silver nanoparticles in a rabbit model. *J Periodontal Implant Sci.* 2012;42(5):175–182.
34. Padmavathy N, Vijayaraghavan R. Enhanced bioactivity of zinc oxide–coated orthodontic mini-implants. *Indian J Dent Res.* 2015;26(5):521–526.
35. Liao J, Li Y, Yang L, Li W, Peng H. A novel chitosan-based nano-coating for orthodontic mini-implants: antibacterial and bone response evaluation. *Mater Sci Eng C Mater Biol Appl.* 2017;70(Pt 1):427–435.