WEP
Warwick
Evans
Publishing

International Journal of Public Health and Medical Research
ISSN: 3006-7707 (Print), ISSN: 3006-3752 (Online) | Volume 4, Number 3, Year 2025
DOI: https://doi.org/10.62051/ijphmr.v4n3.02
Journal homepage: https://wepub.org/index.php/IJPHMR/index

Research Progress on Antimicrobial Surface Modification Materials for Dental Implants

Fei Meng *, Yang Chen

North China University of Science and Technology, Tangshan 063000, China

ABSTRACT

Peri-implantitis is one of the main reasons for the failure of dental implants. Traditional implant surfaces lack antimicrobial properties and are prone to bacterial infections. In recent years, antimicrobial surface modification technologies for implants have become a research hotspot. These technologies endow implants with antimicrobial functions through physical, chemical, or biological methods to improve long-term success rates. This paper reviews the main strategies for antimicrobial surface modification of implants (such as antimicrobial coatings, nanostructural modifications, ion doping, and bioactive molecule loading), analyzes the advantages and disadvantages of different methods, and explores future development directions to provide a theoretical basis for the design of clinical implants.

KEYWORDS

Peri-implantitis; Implants; Antimicrobial

1. INTRODUCTION

Dental implants have shown significant advantages in repairing missing teeth, but peri-implantitis remains the main complication affecting their long-term stability. Studies have shown that the formation of bacterial biofilms on implant surfaces is a key factor in triggering inflammation [1]. Therefore, the development of implant surface modification materials with antimicrobial functions has become a current research focus. This paper systematically summarizes the research progress in antimicrobial surface modification of implants in recent years and looks forward to future trends.

2. MAIN STRATEGIES FOR ANTIMICROBIAL SURFACE MODIFICATION OF IMPLANTS

Antimicrobial Coating TechnologyAntimicrobial coatings achieve antibacterial effects by depositing antimicrobial agents (such as antibiotics, silver nanoparticles, chitosan, etc.) on the implant surface. These coatings can significantly reduce bacterial colonization and subsequent infection, thereby enhancing the overall performance and longevity of dental implants.• Silver Nanoparticles (AgNPs) Coating: AgNPs have broad-spectrum antibacterial properties and can kill bacteria by disrupting bacterial cell membranes [1]. However, long-term release may cause cytotoxicity, which can adversely affect surrounding tissues and cells [2].• Chitosan (Chitosan) Coating: Chitosan is biocompatible and has antimicrobial properties. It can carry antimicrobial drugs (such as chlorhexidine) to achieve sustained release, providing long-lasting antibacterial effects. This coating not only inhibits bacterial growth but also promotes tissue healing and integration with the implant surface.

Nanostructural Surface ModificationNanostructured surfaces are created through various techniques, such as anodic oxidation and sandblasting followed by acid etching (SLA), to reduce bacterial adhesion. These modifications can enhance the surface properties of implants, making them less conducive to bacterial colonization and more favorable for osseointegration.• TiO_2 Nanotube Arrays: These structures can carry antibiotics or AgNPs and have demonstrated both antimicrobial and osteogenic properties [1]. The combination of these functions can improve the overall performance of dental implants by reducing the risk of infection and promoting bone formation around the implant.• Biomimetic Micro-Nano Structures: By mimicking the surface texture of shark skin (Sharklet™), these structures can physically inhibit bacterial colonization [2]. This approach leverages the natural antibacterial properties of certain surface textures to reduce the risk of infection without the need for chemical antimicrobial agents.

Ion Doping ModificationAntibacterial metal ions (such as Zn^{2+}, Cu^{2+}, F^{-}) are doped into the surface of titanium implants to enhance their antimicrobial properties. This method can provide long-lasting antimicrobial effects while also promoting osseointegration.• Zn^{2+} Doping: Zinc ions can inhibit bacterial metabolism while simultaneously promoting the differentiation of osteoblasts (Zhang et al., 2023). This dual functionality makes Zn^{2+} doping a promising approach for improving implant performance by reducing the risk of infection and enhancing bone formation.• Cu^{2+} Doping: Copper ions have strong antibacterial properties, but high concentrations may inhibit bone formation [3]. Therefore, careful control of ion concentration is necessary to balance antimicrobial efficacy with biocompatibility.

Bioactive Molecule LoadingAntimicrobial peptides (AMPs), lysozyme, and other biomolecules are fixed through covalent bonding or physical adsorption. These bioactive molecules can provide targeted antimicrobial effects and promote tissue healing.• Antimicrobial Peptides (AMPs): Such as LL-37, which can selectively kill pathogens without damaging host cells. This selective action reduces the risk of cytotoxicity and promotes a more favorable healing environment.• Photodynamic Antimicrobial (aPDT) Coating: Using photosensitizers (such as methylene blue) to produce reactive oxygen species (ROS) under light to kill bacteria. This method provides a non-invasive and effective way to eliminate bacteria while minimizing damage to surrounding tissues.

3. CURRENT CHALLENGES AND LIMITATIONS

Insufficient Antimicrobial Durability: The antibacterial effect of most coatings gradually weakens after the release of antimicrobial agents [3]. This limitation necessitates the development of more durable and long-lasting antimicrobial coatings. Many current coatings rely on the controlled release of antimicrobial agents, but once these agents are depleted, the surface loses its antimicrobial properties. This can leave the implant vulnerable to bacterial colonization over time, potentially leading to peri-implantitis. Therefore, there is a need for innovative approaches to ensure that antimicrobial activity is sustained throughout the life of the implant.

Balancing Biocompatibility: Agents like AgNPs and Cu^{2+} may inhibit bone formation at high concentrations [3]. Achieving a balance between antimicrobial efficacy and biocompatibility is crucial for the success of implant surface modifications. While these agents are highly effective at killing bacteria, their cytotoxic effects on osteoblasts and other cells involved in bone formation can compromise the long-term stability of the implant. Researchers must carefully optimize the concentration and delivery mechanisms of these agents to maximize their antimicrobial benefits while minimizing adverse effects on bone integration.

Difficult Clinical Translation: Laboratory results are hard to scale up for production, and long-term clinical data are lacking [4]. Bridging the gap between laboratory research and clinical application is a significant challenge that requires collaborative efforts from researchers, manufacturers, and clinicians. Many promising antimicrobial surface modifications that show excellent results in the lab face hurdles when it comes to large-scale production and real-world clinical use. Ensuring that these technologies can be reliably and consistently produced at scale, while also gathering sufficient long-term clinical data to validate their effectiveness and safety, is essential for their widespread adoption.

4. FUTURE DEVELOPMENT DIRECTIONS

Smart Responsive Coatings: Develop pH/enzyme-responsive antimicrobial agents that release only in the infected microenvironment [5]. These smart coatings can provide targeted antimicrobial effects, reducing the risk of cytotoxicity and promoting a more favorable healing environment. By designing coatings that respond to specific triggers, such as changes in pH or the presence of bacterial enzymes, it is possible to release antimicrobial agents only when and where they are needed. This targeted approach can minimize the potential for cytotoxicity and ensure that the antimicrobial properties are preserved for as long as necessary.

Multifunctional Composite Modifications: Combine antimicrobial, osteogenic, and anti-inflammatory functions (e.g., Mg^{2+} + AMP co-modification). This multifunctional approach can enhance the overall performance of dental implants by addressing multiple aspects of implant success. By integrating multiple functionalities into a single surface modification, it is possible to not only prevent bacterial infection but also promote bone formation and reduce inflammation. This comprehensive approach can significantly improve the long-term stability and success rate of dental implants.

3D Printed Personalized Implants: Combine topological optimization with antimicrobial modification to achieve precise treatment [5]. 3D printing technology allows for the creation of customized implants that can be tailored to individual patient needs, improving the fit and functionality of dental implants. By leveraging 3D printing, it is possible to create implants with optimized surface topographies that enhance osseointegration while also incorporating antimicrobial modifications. This personalized approach can lead to better clinical outcomes by ensuring that each implant is specifically designed to meet the unique requirements of each patient.

5. CONCLUSION

Antimicrobial surface modification materials for dental implants show great potential in preventing peri-implantitis, but there are still challenges to be addressed regarding antimicrobial durability, biocompatibility, and clinical applicability. These challenges are multifaceted and require a comprehensive approach to overcome. For instance, ensuring that the antimicrobial properties of these materials can be maintained over the long term is crucial for the success of dental implants. Many current antimicrobial coatings and modifications tend to lose their effectiveness over time, which can lead to an increased risk of infection. Therefore, developing materials that can sustain their antimicrobial activity throughout the life of the implant is a key area of focus.Moreover, achieving a balance between antimicrobial efficacy and biocompatibility is essential. Some of the most effective antimicrobial agents, such as certain metal ions and nanoparticles, can have cytotoxic effects on surrounding tissues at high concentrations. This can hinder the integration of the implant with the surrounding bone and soft tissues, potentially leading to implant failure. Thus, researchers are working on optimizing the concentration and delivery of these agents to maximize their antimicrobial benefits while minimizing any adverse effects on tissue health.In the future, smart responsive materials, multifunctional composite coatings, and advanced manufacturing technologies (such as 3D printing) will become research focuses, promoting the clinical application of antimicrobial implants. Smart responsive materials, for example, can release antimicrobial agents only in response to specific triggers, such as changes in pH or the presence of bacterial enzymes. This targeted approach can reduce the risk of cytotoxicity and ensure that antimicrobial properties are preserved for as long as necessary. Multifunctional composite coatings, on the other hand, can combine antimicrobial, osteogenic, and anti-inflammatory functions, enhancing the overall performance of dental implants by addressing multiple aspects of implant success. Additionally, 3D printing technology allows for the creation of customized implants that can be tailored to individual patient needs, improving the fit and functionality of dental implants.Continued research and development in these areas will contribute to the advancement of dental implant technology and improve patient outcomes. By addressing the current limitations and exploring innovative solutions, researchers and clinicians can work together to develop dental implants that are not only highly effective at preventing infection but also promote long-term stability and integration with the surrounding tissues. This collaborative effort will involve interdisciplinary approaches, combining materials science, biology, and clinical dentistry to create implants that meet the highest standards of safety and efficacy.Ultimately, these advancements will lead to better clinical outcomes and improved quality of life for patients receiving dental implants. Patients will benefit from implants that are less likely to fail due to infection, have a longer lifespan, and provide a more comfortable and functional restoration of their oral health. As research progresses and new technologies are developed, the field of dental implantology will continue to evolve, offering patients more reliable and effective solutions for tooth replacement.

REFERENCES

[1] Wang M, Jiang X, Wu C, et al. Application of hyaluronic acid in dental tissue regeneration [J]. Journal of biomedical materials research. Part A, 2018, 106(4): 996-1002.

[2] Tsukada Y, Nakamura R, Akazawa K, et al. Hyaluronic acid promotes epithelial migration during wound healing in vitro [J]. Journal of periodontology, 2019, 90(7): 784-792.

[3] Vignesh R, Sudhakar U, Uma K. Role of Platelet rich fibrin and hyaluronic acid in surgical management of endo-periodontal lesion: A case report [J]. Journal of oral biology and craniofacial research, 2020, 10(1): 115-118.

[4] Sydiskis R, Owen D G, Lohr J L, et al. Inactivation of enveloped viruses by anthraquinones extracted from plants [J]. Antimicrobial agents and chemotherapy, 1991, 35(12): 2463-2466.

[5] Hocevar B J, Mohoric L, Kos J. Hyaluronan modulates TRAIL-resistance in colon cancer cells through STAT3 activation [J]. Experimental cell research, 2012, 318(2): 117-125.