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BIOMIMETIC SURFACE MODIFICATIONS IN MEDICAL AND DENTAL IMPLANTS: A PARADIGM SHIFT TOWARD INTELLIGENT BIOMATERIALS

MODIFICAÇÕES DE SUPERFÍCIE BIOMIMÉTICAS EM IMPLANTES MÉDICOS E ODONTOLÓGICOS: UMA MUDANÇA DE PARADIGMA EM DIREÇÃO A BIOMATERIAIS INTELIGENTES

MODIFICACIONES DE SUPERFICIE BIOMIMÉTICAS EN IMPLANTES MÉDICOS Y DENTALES: UN CAMBIO DE PARADIGMA HACIA BIOMATERIALES INTELIGENTES

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ABSTRACT

Objective: This review aimed to analyze the evidence on the development and effectiveness of long-acting antibacterial dental adhesives for preventing secondary caries and restoration failure.

Methodology: Searches were performed in PubMed, Web of Science, and Google Scholar using the terms "antibacterial dental adhesive", "nanoparticles", "titanium dioxide", and "caries

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prevention". After duplicate elimination, studies were screened by title and abstract, and full texts were evaluated for inclusion. Eligible studies reported antibacterial mechanisms, bonding performance, and durability of adhesive systems.

Results: The integration of titanium dioxide nanoparticles and reactive oxygen species release demonstrated long-lasting antibacterial effects without compromising mechanical adhesion. Data revealed substantial reduction in bacterial infiltration and enhanced longevity of restorations.

Conclusion: Long-acting antibacterial dental adhesives represent a major innovation in restorative dentistry. By combining nanotechnology and sustained antimicrobial action, these materials can significantly reduce restoration failure rates and global caries-related healthcare costs.

Keywords: Antibacterial Dental Adhesive. Titanium Dioxide Nanoparticles. Reactive Oxygen Species. Secondary Caries Prevention.

RESUMO
Objetivo: Esta revisão teve como objetivo analisar as evidências sobre o desenvolvimento e a eficácia de adesivos dentários antibacterianos de longa duração na prevenção de cárie secundária e falhas restauradoras.

Metodologia: As buscas foram realizadas nas bases de dados PubMed, Web of Science e Google Scholar, utilizando os termos "antibacterial dental adhesive", "nanoparticles", "titanium dioxide" e "caries prevention". Após a eliminação de duplicatas, os estudos foram triados por título e resumo, e os textos completos foram avaliados para inclusão. Os estudos elegíveis relataram mecanismos antibacterianos, desempenho de adesão e durabilidade dos sistemas adesivos.

Resultados: A incorporação de nanopartículas de dióxido de titânio e a liberação de espécies reativas de oxigênio demonstraram efeitos antibacterianos duradouros sem comprometer a adesão mecânica. Os dados revelaram redução substancial da infiltração bacteriana e aumento da longevidade das restaurações.

Conclusão: Os adesivos dentários antibacterianos de longa duração representam uma importante inovação na odontologia restauradora. Ao combinar nanotecnologia e ação antimicrobiana sustentada, esses materiais podem reduzir significativamente as taxas de falha restauradora e os custos globais de saúde relacionados à cárie.

Palavras-chave: Adesivo Dentário Antibacteriano. Nanopartículas de Dióxido de Titânio. Espécies Reativas de Oxigênio. Prevenção de Cárie Secundária.

RESUMEN
Objetivo: Esta revisión tuvo como objetivo analizar la evidencia sobre el desarrollo y la eficacia de adhesivos dentales antibacterianos de acción prolongada para la prevención de caries secundaria y el fracaso de las restauraciones.

Metodología: Las búsquedas se realizaron en las bases de datos PubMed, Web of Science y Google Scholar, utilizando los términos "antibacterial dental adhesive", "nanoparticles",

Revista ARACÊ
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"titanium dioxide" y "caries prevention". Tras la eliminación de duplicados, los estudios fueron seleccionados mediante la lectura de títulos y resúmenes, y los textos completos fueron evaluados para su inclusión. Los estudios elegibles informaron sobre los mecanismos antibacterianos, el desempeño de adhesión y la durabilidad de los sistemas adhesivos.

Resultados: La incorporación de nanopartículas de dióxido de titanio y la liberación de especies reactivas de oxígeno demostraron efectos antibacterianos duraderos sin comprometer la adhesión mecánica. Los datos revelaron una reducción sustancial de la infiltración bacteriana y una mayor longevidad de las restauraciones.

Conclusión: Los adhesivos dentales antibacterianos de acción prolongada representan una innovación relevante en la odontología restauradora. Al combinar nanotecnología y acción antimicrobiana sostenida, estos materiales pueden reducir significativamente las tasas de fracaso restaurador y los costos globales de atención sanitaria relacionados con la caries.

Palabras clave: Adhesivo Dental Antibacteriano. Nanopartículas de Dióxido de Titanio. Especies Reactivas de Oxígeno. Prevención de Caries Secundaria.

1 INTRODUCTION

Smart biomaterials have become one of the most transformative innovations in regenerative dentistry and orthopedic medicine. Unlike traditional passive implant materials, smart biomaterials are engineered to interact dynamically with the biological environment, responding to mechanical, chemical, and biological stimuli to enhance tissue integration. Their design incorporates advanced surface modifications, nanotopographies, bioactive coatings, and controlled-release systems that aim to accelerate bone healing and improve long-term implant stability (Ratner & Hoffman, 2013). These emerging materials address limitations associated with conventional titanium implants, such as inadequate osseointegration in compromised hosts and susceptibility to bacterial colonization.

Surface nanotopography has emerged as a central strategy to influence osteoblast adhesion, proliferation, and differentiation. Nanoscale features on implant surfaces can mimic natural extracellular matrix structures, facilitating cellular recognition and enhancing osteogenic activity (Zhao et al., 2010). Moreover, chemical modifications such as calcium-phosphate coatings, bioactive peptides, and reactive oxygen species–modulating surfaces have demonstrated the ability to further promote osseointegration, particularly in challenging clinical scenarios such as osteoporosis or diabetes (Cooper et al., 2006). Biomaterials capable of releasing osteogenic ions or pharmacological agents in a controlled manner represent another promising class of smart implants.

Recent research has also focused on immunomodulatory biomaterials that shift the peri-implant immune response toward a pro-regenerative profile. By regulating macrophage polarization, these materials can reduce inflammation and enhance bone-to-implant contact (Wang et al., 2018). Despite these promising results, existing studies vary widely in their experimental design, materials tested, and evaluation methods. A systematic synthesis of available evidence is therefore needed to understand which smart biomaterial strategies most effectively enhance osseointegration and how these findings may translate into clinical practice.

2 METHODOLOGY

A search strategy was conducted across PubMed, Web of Science, and Google Scholar to identify studies evaluating smart biomaterials and surface modifications intended to enhance osseointegration. The search strategy used MeSH terms and keywords such as: “smart biomaterials,” “osseointegration,” “nanotopography,” “surface modification,” “implant surfaces," "bioactive coatings," and "bone regeneration." Boolean operators (AND/OR) were used to maximize coverage.

All records were exported into Zotero for screening. Duplicates were removed using automated and manual checking procedures. Titles and abstracts were screened independently by two reviewers. Studies were included if they met the following criteria: (1) evaluated biomaterials or implant surface modifications designed to improve osseointegration; (2) used in vitro, in vivo, or clinical models; and (3) provided measurable outcomes such as bone-to-implant contact, osteogenic marker expression, or biomechanical testing. Exclusion criteria included reviews, book chapters, non-implant-related studies, and papers lacking original experimental data.

Full-text articles passing initial screening were assessed for eligibility. Disagreements between reviewers were resolved by consensus or third-party evaluation. Reference lists of included studies were examined to identify additional relevant publications. Only studies that reported primary data and directly assessed osseointegration-related outcomes were included in the final sample.

3 RESULTS

The analysis of the selected literature reveals a consistent and biologically coherent advantage of biomimetic and smart surface modifications over conventional machined or minimally roughened implant surfaces. The findings can be organized into five major domains: nanotopographical modulation, chemical and ionic surface functionalization, bioactive coatings, immunomodulatory effects, and biomechanical performance.

3.1 NANOTOPOGRAPHICAL SURFACE MODIFICATIONS

Nanostructured implant surfaces demonstrated a clear superiority in promoting early cellular events related to osseointegration. Titanium implants modified with nanotubes, nanopores, or hierarchical micro–nano features consistently enhanced osteoblast adhesion, spreading, and cytoskeletal organization compared with smooth or purely microscale surfaces. Multiple in vitro studies reported increased expression of osteogenic markers, including alkaline phosphatase (ALP), runt-related transcription factor 2 (Runx2), osteocalcin, and collagen type I, indicating accelerated osteogenic differentiation on nanotopographically modified surfaces (Zhao et al., 2010).

Animal studies corroborated these cellular findings, showing significantly greater bone-to-implant contact (BIC) around nanotextured implants during early healing phases. Histomorphometric analyses revealed that micro–nano hybrid surfaces outperformed either microscale or nanoscale modifications alone, suggesting a synergistic effect between different length scales of surface architecture. These surfaces more closely replicate the hierarchical organization of native bone extracellular matrix, thereby facilitating osteoblast recognition and attachment.

3.2 CHEMICAL AND IONIC SURFACE FUNCTIONALIZATION

Surface chemistry emerged as a critical determinant of biological performance. Implants modified with osteogenic ions such as calcium, phosphate, magnesium, strontium, and fluoride demonstrated enhanced mineralization and improved bone maturation. Fluoride-modified titanium surfaces, in particular, showed increased osteoblast proliferation and differentiation, as well as stronger bone anchorage in vivo (Cooper et al., 2006).

Ion-doped surfaces exhibited not only enhanced osteogenic responses but also improved early-stage bone formation kinetics. Several studies reported higher mineral apposition rates and increased trabecular density adjacent to ion-functionalized implants compared with untreated controls. These effects were attributed to the direct stimulation of osteogenic signaling pathways and improved protein adsorption profiles at the implant interface.

3.3 BIOACTIVE COATINGS AND CONTROLLED RELEASE SYSTEMS

Bioactive coatings such as hydroxyapatite, calcium phosphate, and composite biomimetic layers significantly improved osseointegration outcomes. Compared with bare titanium, coated implants showed higher BIC values, improved interfacial strength, and more homogeneous bone deposition along the implant surface. Quantitative data from animal models demonstrated BIC increases ranging from approximately 15% to over 35%, depending on coating composition and evaluation time point.

Advanced smart coatings incorporating controlled-release systems further enhanced biological performance. These systems enabled sustained local delivery of osteogenic ions or bioactive molecules, maintaining long-term stimulatory effects without compromising surface stability. Removal torque and push-out tests consistently showed higher mechanical

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stability for implants with controlled-release coatings, indicating stronger bone–implant integration over time.

3.4 IMMUNOMODULATORY SURFACE EFFECTS

A growing body of evidence highlights the role of immune modulation in osseointegration. Biomimetic surfaces engineered to influence macrophage behavior demonstrated a consistent shift from a pro-inflammatory M1 phenotype toward a pro-regenerative M2 phenotype. This polarization was associated with reduced expression of inflammatory cytokines and increased secretion of growth factors conducive to bone regeneration (Wang et al., 2018).

In vivo studies showed that immunomodulatory surfaces reduced early inflammatory responses at the implant site and promoted a more favorable healing microenvironment. This effect was particularly evident during the critical early healing phase, where excessive inflammation is known to impair osseointegration. Enhanced bone formation and more stable bone–implant interfaces were observed in association with these immune-regulating strategies.

3.5 BIOMECHANICAL PERFORMANCE AND LONG-TERM STABILITY

From a mechanical standpoint, biomimetic and smart surface modifications resulted in superior implant stability. Removal torque, pull-out, and push-in tests consistently demonstrated higher values for modified implants compared with conventional surfaces. These improvements were observed both in early healing stages and during long-term follow-up in animal models.

Importantly, studies evaluating durability reported that advanced surface modifications did not compromise mechanical integrity or fatigue resistance. Instead, the enhanced biological integration translated into improved functional stability, supporting the clinical relevance of these surface engineering strategies.

4 DISCUSSION

The results collectively demonstrate that biomimetic surface modifications fundamentally alter the biological and mechanical behavior of medical and dental implants. Rather than acting as passive substrates, these surfaces actively participate in regulating cellular responses, immune behavior, and tissue regeneration. This represents a conceptual shift from traditional implant design toward a biologically driven, interactive paradigm.

The superiority of nanotopographical modifications underscores the importance of surface architecture in cellular mechanotransduction. Cells do not merely adhere to implant surfaces; they actively sense and respond to nanoscale cues that influence cytoskeletal tension, gene expression, and lineage commitment. Hierarchical micro–nano designs appear particularly effective because they integrate mechanical stability with biologically relevant nanoscale signaling, closely mimicking native bone structure.

Chemical and ionic functionalization further amplifies these effects by directly modulating the biochemical environment at the implant interface. The consistent enhancement of osteogenesis observed with ion-doped surfaces suggests that local ionic signaling plays a critical role in bone formation. These findings challenge the notion that osseointegration is driven solely by surface roughness and highlight the need to consider surface chemistry as an equally important design parameter.

The emergence of immunomodulatory surfaces marks a significant advancement in implant science. Osseointegration is increasingly recognized as an immune-regulated process rather than a purely osteogenic one. By actively guiding macrophage polarization, smart surfaces help establish a regenerative microenvironment that favors bone formation over fibrous encapsulation. This approach is particularly relevant for patients with systemic inflammatory conditions, where impaired immune regulation often compromises implant success.

Despite these promising findings, the translational gap between experimental models and clinical application remains substantial. Many studies rely on short-term animal models with controlled conditions that do not fully replicate the complexity of human clinical scenarios. Variability in surface fabrication techniques, outcome measures, and experimental designs further limits direct comparison between studies and complicates evidence synthesis.

Another critical issue is the tendency of some studies to overinterpret early biological advantages as indicators of long-term clinical success. While enhanced early osseointegration is undoubtedly beneficial, it does not automatically guarantee improved long-term implant survival. Factors such as mechanical loading, microbial challenge, and patient-specific variables must be considered before extrapolating laboratory findings to clinical outcomes.

Revista ARACÊ
ISSN: 2358-2472

Future implant designs will likely move toward multifunctional surfaces that integrate nanotopography, bioactive chemistry, controlled-release systems, and immunomodulatory properties into a single platform. However, achieving this integration without compromising manufacturing scalability, mechanical reliability, or regulatory approval remains a significant challenge. Rigorous long-term clinical trials are essential to validate whether these advanced biomimetic strategies translate into meaningful improvements in implant longevity and patient outcomes.

5 CONCLUSION

Long-acting antibacterial dental adhesives represent a major innovation in restorative dentistry. By combining nanotechnology and sustained antimicrobial action, these materials can significantly reduce restoration failure rates and global caries-related healthcare costs.

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