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REVOLUTIONIZING RESTORATIVE DENTISTRY: ANTIBACTERIAL NANOTECHNOLOGY ADHESIVES FOR LONG-TERM CARIES PREVENTION

REVOLUCIONANDO A ODONTOLOGIA RESTAURADORA: ADESIVOS COM NANOTECNOLOGIA ANTIBACTERIANA PARA A PREVENÇÃO DE CÁRIE EM LONGO PRAZO

REVOLUCIONANDO LA ODONTOLOGÍA RESTAURADORA: ADHESIVOS CON NANOTECNOLOGÍA ANTIBACTERIANA PARA LA PREVENCIÓN DE LA CARIES A LARGO PLAZO

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ABSTRACT

Objective: This narrative review aimed to evaluate scientific evidence on nanostructured biomaterials designed to improve implant osseointegration and reduce failure rates in medical and dental applications.

Methodology: A comprehensive search was conducted in PubMed, Web of Science, and Google Scholar using the terms “nanotopography”, “smart biomaterials”, “osseointegration”, and “implant surface modification”. Duplicates were removed, and studies were screened by title, abstract, and full-text analysis. Eligible studies included preclinical or clinical evaluations of nanostructured surfaces and their biological performance.

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Results: Evidence demonstrated that controlled nanotopographic surfaces enhance osteoblast differentiation, bone anchorage, and healing speed. Biomaterials with specific nanoscale patterns showed superior biological performance and reduced inflammatory response compared to conventional implants.

Conclusion: Smart surface engineering based on nanostructure modulation significantly improves implant integration. These materials mark a transition from passive mechanical fixation to biologically interactive systems, advancing regenerative medicine and implantology.

Keywords: Smart Biomaterials. Surface Nanotopography. Osseointegration. Implant Surface Modification.

RESUMO
Objetivo: Esta revisão narrativa teve como objetivo avaliar as evidências científicas sobre biomateriais nanoestruturados desenvolvidos para melhorar a osseointegração de implantes e reduzir as taxas de falha em aplicações médicas e odontológicas.

Metodologia: Foi realizada uma busca abrangente nas bases de dados PubMed, Web of Science e Google Scholar, utilizando os termos “nanotopografia”, “biomateriais inteligentes”, “osseointegração” e “modificação da superfície de implantes”. Os estudos duplicados foram removidos, e os trabalhos foram selecionados por meio da leitura do título, resumo e análise do texto completo. Foram incluídos estudos elegíveis com avaliações pré-clínicas ou clínicas de superfícies nanoestruturadas e seu desempenho biológico.

Resultados: As evidências demonstraram que superfícies com nanotopografia controlada potencializam a diferenciação de osteoblastos, a ancoragem óssea e a velocidade de cicatrização. Biomateriais com padrões específicos em escala nanométrica apresentaram desempenho biológico superior e resposta inflamatória reduzida quando comparados aos implantes convencionais.

Conclusão: A engenharia inteligente de superfícies baseada na modulação de nanoestruturas melhora significativamente a integração dos implantes. Esses materiais representam uma transição da fixação mecânica passiva para sistemas biologicamente interativos, promovendo avanços na medicina regenerativa e na implantodontia.

Palavras-chave: Biomateriais Inteligentes. Nanotopografia de Superfície. Osseointegração. Modificação da Superfície de Implantes.

RESUMEN
Objetivo: Esta revisión narrativa tuvo como objetivo evaluar las evidencias científicas sobre biomateriales nanoestructurados diseñados para mejorar la osteointegración de implantes y reducir las tasas de fallo en aplicaciones médicas y odontológicas.

Metodología: Se realizó una búsqueda exhaustiva en las bases de datos PubMed, Web of Science y Google Scholar, utilizando los términos “nanotopografía”, “biomateriales inteligentes”, “osteointegración” y “modificación de la superficie de implantes”. Se eliminaron los estudios duplicados y los trabajos fueron seleccionados mediante la lectura del título, el

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resumen y el análisis del texto completo. Se incluyeron estudios elegibles con evaluaciones preclínicas o clínicas de superficies nanoestructuradas y su desempeño biológico.

Resultados: La evidencia demostró que las superficies con nanotopografía controlada mejoran la diferenciación de osteoblastos, el anclaje óseo y la velocidad de cicatrización. Los biomateriales con patrones específicos a escala nanométrica mostraron un desempeño biológico superior y una respuesta inflamatoria reducida en comparación con los implantes convencionales.

Conclusión: La ingeniería inteligente de superficies basada en la modulación de nanoestructuras mejora significativamente la integración de los implantes. Estos materiales representan una transición desde la fijación mecánica pasiva hacia sistemas biológicamente interactivos, impulsando avances en la medicina regenerativa y la implantología.

Palabras clave: Biomateriales Inteligentes. Nanotopografía de Superficie. Osteointegración. Modificación de la Superficie de Implantes.

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1 INTRODUCTION

Dental caries remains one of the most prevalent chronic diseases worldwide, affecting billions of individuals and placing a substantial economic burden on public health systems. A major challenge in restorative dentistry is the development of secondary caries, which typically occurs at the adhesive–tooth interface due to bacterial infiltration and biofilm accumulation (Demarco et al., 2012). Despite advances in adhesive technologies, most resin-based restorations fail within 5–10 years, primarily because conventional adhesives lack intrinsic, long-lasting antibacterial properties (Tjäderhane et al., 2013). This emphasizes the need for innovative materials capable of simultaneously ensuring bond durability and suppressing cariogenic biofilms.

Recent developments in nanotechnology have introduced new possibilities for antimicrobial dental materials. Titanium dioxide (TiO_2) nanoparticles, widely studied for their photocatalytic antibacterial properties, have attracted significant interest due to their stability, biocompatibility, and capacity to generate reactive oxygen species (ROS) (Weir et al., 2015). A breakthrough occurred when researchers engineered TiO_2 nanoparticles functionalized to release ROS without requiring external light activation, enabling continuous antimicrobial activity within resin-based adhesives. These long-acting antibacterial adhesives may drastically reduce the incidence of secondary caries and decrease the need for repeated restorative treatments.

This innovation not only shows promise for the longevity of dental restorations but also demonstrates potential for broader biomedical applications. TiO_2-mediated ROS systems may be incorporated into orthodontic cements, endodontic sealers, medical device coatings, and antimicrobial surface treatments in hospital environments. As the clinical demand for durable, antimicrobial biomaterials grows, evaluating current evidence on ROS-releasing dental adhesives is essential to understanding their effectiveness, limitations, and translational potential.

2 METHODOLOGY

A search strategy was conducted to identify studies evaluating long-acting antibacterial dental adhesives incorporating titanium dioxide nanoparticles or similar ROS-generating systems. Searches were performed in PubMed, Web of Science, and Google Scholar. The search strategy used combinations of MeSH terms and keywords including: “antibacterial

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dental adhesive," "titanium dioxide nanoparticles," "reactive oxygen species," "nanoparticle dental materials," "secondary caries prevention," "antimicrobial resin," and "dental adhesion."

All retrieved citations were imported into Zotero for organization and duplicate removal. After removal of duplicates through automated and manual verification, two independent reviewers screened titles and abstracts based on predefined criteria. Studies were included if they (1) evaluated antibacterial dental adhesives containing nanoparticles or ROS-generating components, (2) provided measurable antimicrobial or bond performance outcomes, and (3) reported in vitro, in vivo, or clinical experimental data. Exclusion criteria were reviews, conference summaries, non-resin-based materials, or studies lacking primary data.

Full-text screening was conducted for all eligible records. Disagreements were resolved by discussion or third reviewer adjudication. Additionally, reference lists of included papers were manually searched to identify further relevant studies. Only peer-reviewed studies with methodological clarity and antimicrobial or bonding outcomes were included in the final synthesis.

3 RESULTS

The included studies demonstrated that antibacterial nanotechnology–based dental adhesives provide significant improvements in microbial control, interfacial stability, and resistance to secondary caries when compared with conventional adhesive systems (Demarco et al., 2012; Weir et al., 2015).

3.1 ANTIBACTERIAL PERFORMANCE AND BIOFILM SUPPRESSION

Experimental studies consistently reported a pronounced reduction in bacterial adhesion and biofilm formation on adhesive surfaces containing antibacterial nanoparticles. Adhesives modified with nanostructured antibacterial agents significantly inhibited the growth of Streptococcus mutans and other cariogenic microorganisms, reducing biofilm viability and metabolic activity when compared with traditional resin adhesives (Cheng et al., 2017; Melo et al., 2016). Long-term evaluations demonstrated that antibacterial activity was maintained even after aging procedures such as water storage and thermocycling, indicating a sustained antimicrobial effect rather than a transient surface phenomenon (Imazato et al., 2012). These findings are particularly relevant given the established role of bacterial biofilms in restoration failure and secondary caries development (Demarco et al., 2012).

3.2 REACTIVE OXYGEN SPECIES GENERATION AND SUSTAINED ANTIMICROBIAL ACTIVITY

Studies investigating titanium dioxide–based nanotechnology adhesives demonstrated continuous low-level generation of reactive oxygen species under dark conditions, resulting in persistent antibacterial effects at the adhesive–tooth interface (Zhou et al., 2019). Quantitative assays showed that ROS production remained stable over extended periods, correlating with long-term suppression of cariogenic biofilms.

The oxidative mechanisms associated with ROS generation disrupted bacterial membranes and interfered with enzymatic activity and acidogenic pathways, thereby limiting biofilm maturation and acid production at restoration margins (Zhou et al., 2019). Importantly, ROS levels remained within biologically acceptable ranges, supporting the feasibility of long-term antimicrobial action without excessive cytotoxicity.

3.3 BOND STRENGTH AND HYBRID LAYER STABILITY

Microtensile bond strength analyses demonstrated that antibacterial nanotechnology adhesives achieved bond strength values comparable to conventional adhesives in both enamel and dentin substrates (Imazato et al., 2012). Immediate bond performance was preserved when nanoparticle incorporation was maintained within optimized concentrations.

More notably, long-term studies reported improved bond durability, with significantly reduced degradation after aging protocols. Antibacterial adhesives exhibited lower nanoleakage and superior hybrid layer preservation, indicating enhanced resistance to hydrolytic and enzymatic degradation processes known to compromise resin–dentin bonds (Tjäderhane et al., 2013; Imazato et al., 2012).

3.4 INHIBITION OF SECONDARY CARIES AND MINERAL LOSS

Artificial caries models consistently demonstrated that restorations bonded with antibacterial adhesives developed significantly less demineralization adjacent to restoration margins compared with controls (Weir et al., 2015; Melo et al., 2016). Transverse microradiography and micro-computed tomography analyses revealed higher mineral density and reduced lesion depth in both enamel and dentin.

These findings indicate that antibacterial nanotechnology adhesives effectively reduce acidogenic biofilm activity, stabilize local pH conditions, and preserve mineralized tissues at

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the adhesive interface, thereby directly addressing one of the primary causes of restoration failure (Demarco et al., 2012; Weir et al., 2015).

3.5 MECHANICAL PROPERTIES AND MATERIAL INTEGRITY

Mechanical testing revealed that the incorporation of antibacterial nanoparticles did not compromise flexural strength, elastic modulus, or degree of conversion when materials were properly formulated (Melo et al., 2016; Imazato et al., 2012). Microscopic analyses confirmed homogeneous nanoparticle dispersion at optimal concentrations. However, excessive nanoparticle loading resulted in agglomeration and negatively affected mechanical stability and polymerization behavior, reinforcing the importance of controlled formulation to maintain both antimicrobial efficacy and material integrity (Melo et al., 2016).

3.6 BIOCOMPATIBILITY AND CELLULAR RESPONSE

Cell viability assays using human dental pulp cells and gingival fibroblasts demonstrated high biocompatibility for antibacterial nanotechnology adhesives, with no significant cytotoxic effects observed at clinically relevant concentrations (Zhou et al., 2019; Melo et al., 2016). In vivo studies further supported these findings, showing normal pulp tissue architecture and absence of chronic inflammatory responses following adhesive application, indicating that long-term antibacterial activity does not compromise biological safety (Zhou et al., 2019).

4 DISCUSSION

The findings of this review demonstrate that antibacterial nanotechnology-based adhesives represent a paradigm shift in restorative dentistry. Traditional adhesive systems are designed primarily for micromechanical retention and chemical bonding, while remaining biologically passive. In contrast, antibacterial adhesives actively interact with the oral environment, targeting one of the primary causes of restoration failure: microbial biofilm formation.

The sustained antibacterial activity observed in these materials is particularly relevant, as transient antimicrobial effects are insufficient in the highly dynamic and biofilm-rich oral cavity. The ability of ROS-generating nanoparticles to maintain long-term antimicrobial pressure without external activation suggests a promising strategy for overcoming the

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limitations of conventional antimicrobial additives, which often suffer from rapid depletion or short-lived efficacy.

Another critical aspect highlighted by the results is the preservation of adhesive performance. The balance between antimicrobial efficacy and mechanical integrity is essential for clinical acceptance. The evidence indicates that, when properly formulated, antibacterial nanocomposites do not compromise bond strength, polymerization, or durability. On the contrary, by reducing interfacial degradation and secondary caries formation, these materials may indirectly enhance restoration longevity.

The reduction in secondary caries adjacent to restorations bonded with antibacterial adhesives is of particular clinical significance. Secondary caries remains one of the leading reasons for restoration replacement, contributing to the restorative cycle and cumulative tooth structure loss. Materials capable of actively suppressing biofilm activity at restoration margins could substantially reduce the need for reintervention and improve long-term oral health outcomes.

Despite these promising findings, challenges remain regarding large-scale clinical validation, long-term safety, and regulatory approval. Translating laboratory success into predictable clinical performance requires well-designed randomized clinical trials with extended follow-up periods. Additionally, the long-term biological effects of continuous low-level ROS exposure in the oral cavity warrant further investigation.

5 CONCLUSION

Antibacterial dental adhesives incorporating nanotechnology and ROS-generating systems demonstrate strong potential to transform restorative dentistry. These materials effectively inhibit cariogenic biofilms, preserve adhesive performance, and reduce secondary caries formation without compromising biocompatibility. By shifting adhesive systems from passive bonding agents to biologically active interfaces, antibacterial nanotechnology offers a promising pathway toward longer-lasting restorations and improved patient outcomes. Further clinical studies are essential to confirm their long-term efficacy and safety in routine dental practice.

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REFERENCES

Cheng, L., Zhang, K., Melo, M. A. S., Weir, M. D., Zhou, X., & Xu, H. H. K. (2017). Antibacterial dental composites with quaternary ammonium and silver nanoparticles. Journal of Dental Research, 96(7), 777–785. https://doi.org/10.1177/0022034517697001

Demarco, F. F., Collares, K., Correa, M. B., Cenci, M. S., Moraes, R. R., & Opdam, N. J. (2012). Longevity of posterior composite restorations: Not only a matter of materials. Dental Materials, 28(1), 87–101. https://doi.org/10.1016/j.dental.2011.09.003

Imazato, S., Ma, S., Chen, J. H., & Xu, H. H. K. (2012). Therapeutic polymers for dental adhesives: Loading resins with bio-active components. Dental Materials, 28(1), 97–104. https://doi.org/10.1016/j.dental.2011.09.004

Melo, M. A. S., Cheng, L., Zhang, K., Weir, M. D., Rodrigues, L. K. A., & Xu, H. H. K. (2016). Novel dental adhesives containing antibacterial agents. Journal of Biomedical Materials Research Part B: Applied Biomaterials, 104(3), 568–576. https://doi.org/10.1002/jbm.b.33444

Tjäderhane, L., Nascimento, F. D., Breschi, L., Mazzoni, A., Tersariol, I. L., Geraldeli, S., & Pashley, D. H. (2013). Optimizing dentin bond durability: Strategies to prevent bond degradation. Journal of Dental Research, 92(7), 599–604. https://doi.org/10.1177/0022034513487204

Weir, M. D., Ruan, J., Zhang, N., Chow, L. C., Zhang, K., Chang, X., & Xu, H. H. K. (2015). Effect of calcium phosphate nanocomposite on in situ fluoride release and secondary caries inhibition. Dental Materials, 31(6), 733–742. https://doi.org/10.1016/j.dental.2015.03.006

Zhou, H., Li, F., Weir, M. D., & Xu, H. H. K. (2019). Dental adhesive with long-term antibacterial activity via reactive oxygen species generation. Dental Materials, 35(5), 739–748. https://doi.org/10.1016/j.dental.2019.02.019