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Research Article

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Titanium and zirconia dental implants: biological principles and clinical outcomes

Abstract

Oral rehabilitation of fully or partially edentulous patients remains a major clinical challenge due to functional, esthetic, and biological demands. The introduction of osseointegration in the twentieth century established the biological foundation of modern implant dentistry and enabled predictable long-term outcomes with titanium implants. Continuous advances in implant design, surface characteristics, loading protocols, and biomaterials have expanded clinical possibilities, including the development of zirconia implants as a metal-free alternative. To critically analyze the historical, biological, and technological evolution of dental implants, with particular emphasis on the current clinical role of zirconia implants in evidence-based oral rehabilitation. This systematic review was conducted in accordance with the PRISMA 2020 guidelines. Electronic searches of PubMed/MEDLINE, Scopus, and Web of Science were performed for English-language publications from January 2000 to March 2026. Clinical trials, cohort studies, and systematic reviews evaluating titanium and zirconia dental implants were included. Data regarding implant survival, osseointegration, marginal bone loss, loading protocols, and biological, technical, and esthetic outcomes were qualitatively synthesized. Methodological quality was assessed using RoB 2, ROBINS-I, and AMSTAR-2 tools. Titanium implants consistently demonstrated high long-term survival rates (>90–95%), confirming their status as the gold standard. Zirconia implants showed comparable short- and medium-term survival and marginal bone stability, particularly in one-piece designs. Immediate and early loading protocols achieved outcomes similar to conventional loading when appropriate clinical criteria were respected. Zirconia implants exhibited favorable soft-tissue responses and superior esthetic outcomes in anterior regions, although mechanical limitations were noted in specific designs. Titanium implants remain the most extensively validated option for implant therapy. Zirconia implants represent a viable alternative in selected clinical situations, especially when esthetic demands are prioritized; however, long-term randomized controlled trials are still required to confirm their biological and mechanical predictability.

Keywords: dental implants, titanium, zirconium oxide, implant survival

Volume 17 Issue 2 - 2026

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Received: April 21, 2026 | **Published:** June 04, 2026

Introduction

Oral rehabilitation of fully or partially edentulous patients has long represented a significant clinical challenge in dentistry, encompassing functional, esthetic, and psychosocial implications. Historical evidence indicates that empirical attempts at tooth replacement date back to ancient civilizations; however, the lack of biological and biomechanical foundations resulted in high failure rates. Only in the twentieth century, with advances in scientific research and biomaterials, did it become possible to develop implant systems capable of promoting predictable integration between implant surfaces and bone tissue.[1]

Modern implant dentistry was consolidated following the studies conducted by Per-Ingvar Brånemark, who described a direct, structural, and functional connection between living bone and titanium surfaces, a phenomenon termed osseointegration. This concept became the biological cornerstone of dental implant therapy, enabling high clinical success rates in both single-tooth and extensive rehabilitations.[2,3] Contemporary reviews reinforce that osseointegration is a dynamic process mediated by highly coordinated cellular, molecular, and immunological events.[4]

As scientific knowledge evolved, essential biological criteria for implant success were established, including the achievement of adequate primary stability, limitation of micromovements during the healing phase, and effective control of the peri-implant inflammatory response. Recent studies highlight that failure to meet these parameters compromises bone formation at the bone–implant interface, increasing the risk of early or late implant failure.[4,5]

An improved understanding of peri-implant bone remodeling has demonstrated that the balance between bone resorption and new bone formation is strongly influenced by implant characteristics. Factors such as macrogeometry, micro- and nanotopography, surface energy, and chemical composition play a decisive role in cellular adhesion, osteoblastic differentiation, and long-term marginal bone stability.[6-8] Recent systematic reviews indicate that although surface modifications may enhance early osseointegration, patient- and site-related factors remain the predominant determinants of long-term outcomes.[9]

In parallel, technological advances have enabled the introduction of early and immediate loading protocols, aiming to shorten overall treatment time and improve patient-reported outcomes. Current evidence demonstrates that, when appropriately indicated, these protocols yield survival rates comparable to conventional loading, provided that sufficient primary stability and proper biomechanical control are achieved.[10-12]

In recent years, implant dentistry has also incorporated principles of minimally invasive dentistry and biomimetic esthetics, driving the search for alternatives to titanium. In this context, zirconia-based ceramic implants have emerged as a promising option, particularly in esthetic regions. Clinical studies and recent systematic reviews report that zirconia implants exhibit high biocompatibility, favorable optical properties, reduced bacterial adhesion, and high clinical survival rates, although mechanical limitations compared with titanium persist.[13-16]

Meta-analyses and recent randomized clinical trials suggest that, although titanium remains the gold standard in implant dentistry, zirconia implants demonstrate comparable short- and medium-term clinical performance, especially in anterior areas where esthetic demands are higher.[15-17] Nevertheless, the literature consistently emphasizes the need for long-term randomized controlled studies to better elucidate the biomechanical and biological behavior of zirconia implants under different clinical conditions.[14-16,18-25]

Given this scenario, it is essential to integrate historical evolution, biological principles, and technological advances that have shaped contemporary implant dentistry. Therefore, the aim of this systematic review is to critically analyze the evolution of dental implants, with special emphasis on the current role of zirconia implants in evidence-based oral rehabilitation.

Methodology

Study design and reporting guidelines

This study was designed as a systematic review and conducted in accordance with the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA 2020) guidelines. The entire review process followed a predefined and transparent protocol to ensure methodological rigor, reproducibility, and minimization of selection bias.

Focused question and eligibility criteria

The review question was formulated following the PICO framework: Population (P): Fully or partially edentulous human patients rehabilitated with dental implants; Intervention (I): Implant therapy involving titanium or zirconia dental implants; Comparison (C): Titanium versus zirconia implants, or different implant designs, surface characteristics, and loading protocols when applicable; Outcomes (O): Implant survival and success rates, osseointegration, marginal bone loss, biological and technical complications, and esthetic outcomes.

Clinical studies, randomized controlled trials, prospective and retrospective cohort studies, and systematic reviews addressing these outcomes were considered eligible. Animal studies, in vitro investigations, case reports, technical notes, and narrative reviews were excluded.

Information sources and search strategy

A comprehensive electronic search was performed in the following databases: PubMed/MEDLINE, Scopus, and Web of Science. The search strategy combined controlled vocabulary (MeSH terms) and free-text keywords related to dental implants, osseointegration, surface characteristics, loading protocols, titanium implants, and zirconia implants.

The search was restricted to articles published in English between January 2000 and March 2026, reflecting the period of major technological and biological advances in implant dentistry. Additionally, a manual search of reference lists from selected articles was conducted to identify potentially relevant studies not captured through the electronic search.

Study selection process

All retrieved records were imported into a reference management software, and duplicate articles were removed. Two independent reviewers screened titles and abstracts for eligibility. Articles deemed potentially relevant were subsequently evaluated in full text. Disagreements at any stage were resolved through discussion and consensus between the reviewers. The study selection process is illustrated using a PRISMA flow diagram, detailing the number of records identified, screened, excluded, and included in the qualitative synthesis.

Data extraction

Data were independently extracted by the reviewers using a standardized data extraction form. The collected information included: authorship, year of publication, study design, sample size, implant material and design, surface characteristics, loading protocol, follow-up duration, and reported clinical, radiographic, and biological outcomes.

Risk of bias and quality assessment

The methodological quality of randomized controlled trials was assessed using the Cochrane Risk of Bias Tool (RoB 2), whereas non-randomized studies were evaluated using the ROBINS-I tool. Systematic reviews included for contextual support were assessed using AMSTAR-2. The risk of bias assessments was performed independently by two reviewers, and studies were classified as having low, moderate, or high risk of bias.

Data synthesis

Given the heterogeneity among study designs, implant systems, and outcome measures, a qualitative synthesis was performed. The findings were organized thematically, following the logical structure of implant evolution, biological principles of osseointegration, influence of implant surface characteristics, loading protocols, and the clinical performance of zirconia implants relative to titanium.

Study outcome of literature

Implant survival and success rates

Implant Survival and Success Rates The evaluated literature consistently demonstrated high survival and success rates for dental implants, particularly titanium-based systems, which remain the gold standard in implant dentistry. Long-term survival rates exceeding 90–95% were reported when fundamental biological and biomechanical principles were respected, including adequate primary stability and controlled loading conditions. These findings are strongly supported by classic and contemporary evidence on osseointegration and implant survival outcomes.[1-5]

Zirconia implants, although supported by a smaller volume of long-term clinical evidence, demonstrated promising survival rates in short- and medium-term follow-ups. Recent systematic reviews and meta-analyses reported cumulative survival rates comparable to titanium implants, particularly for one-piece zirconia systems. However, slightly higher rates of early failure and implant fracture were reported, especially in narrow-diameter and two-piece zirconia implants.[13-15,18-25]

Osseointegration and marginal bone loss

Successful osseointegration was identified as a multifactorial biological process influenced by implant material, surface characteristics, and host response. Titanium implants with modified micro- and nano-textured surfaces exhibited enhanced early bone-to-implant contact and predictable secondary stability. Zirconia implants demonstrated comparable osseointegration potential,

Citation: Matos JDM, Batista JPO, Santos IP, et al. Titanium and zirconia dental implants: biological principles and clinical outcomes. *J Dent Health Oral Disord Ther.* 2026;17(2):74–78. DOI: 10.15406/jdhodt.2026.17.00673

although some studies suggested a slower initial bone apposition when compared with roughened titanium surfaces.[1-4,13-15,18-25]

Marginal bone loss values reported across the literature remained within clinically acceptable thresholds for both implant materials. Meta-analytical evidence indicated no statistically significant differences in marginal bone loss between zirconia and titanium implants in short- and medium-term evaluations, reinforcing the biological viability of zirconia implants when proper clinical protocols are followed.[14-17]

Loading protocols

Immediate and early loading protocols demonstrated survival and success rates comparable to those of conventional delayed loading when strict clinical criteria were applied. Adequate insertion torque, favorable bone quality, controlled occlusal loading, and precise surgical execution were consistently identified as key determinants of success. These protocols were associated with reduced treatment time and improved patient satisfaction without an increased incidence of biological complications.[1-12,18-25]

Despite these favorable outcomes, the literature emphasized that improper case selection or insufficient primary stability could compromise osseointegration, underscoring the importance of individualized treatment planning when implementing immediate loading strategies.

Biological, technical, and esthetic outcomes

Biological complications such as peri-implant mucositis and peri-implantitis were reported with similar frequency for titanium and zirconia implants. Some studies suggested lower bacterial adhesion and favorable soft-tissue responses around zirconia implants, potentially contributing to improved peri-implant tissue health.[9,13-16]

From an esthetic perspective, zirconia implants consistently demonstrated superior outcomes, particularly in the anterior region, due to their tooth-like color and reduced risk of mucosal discoloration. Titanium implants, however, continued to exhibit superior mechanical performance, especially in posterior regions subjected to higher occlusal loads.[15-17]

Overall synthesis

Overall, the literature supports titanium implants as the most extensively validated and mechanically reliable option for dental implant therapy. Zirconia implants have emerged as a clinically viable alternative in selected cases, particularly when esthetic demands are paramount. Nevertheless, current evidence underscores the need for long-term randomized controlled trials to further elucidate the biological stability, mechanical reliability, and complication profiles of zirconia implants under diverse clinical conditions.[13-17]

Results

The included studies consistently reported high survival and success rates for dental implants, particularly titanium-based systems, which demonstrated long-term survival rates exceeding 90–95%. These outcomes were strongly associated with the biological principles of osseointegration, including primary stability, controlled micromotion, and adequate host response, confirming titanium as the most extensively validated implant material to date.

Zirconia implants showed favorable clinical outcomes, with short- and medium-term survival rates comparable to titanium implants. Systematic reviews and meta-analyses reported cumulative survival rates above 94%, especially for one-piece zirconia implant systems. Nevertheless, a higher incidence of early failures and implant fractures was observed in narrow-diameter and two-piece zirconia designs.[13-15]

Osseointegration outcomes were significantly influenced by implant surface characteristics and macro-design. Titanium implants with micro- and nano-modified surfaces demonstrated enhanced early bone-to-implant contact and predictable secondary stability. Zirconia implants exhibited comparable osseointegration behavior, although some studies reported slower early bone apposition when compared with roughened titanium surfaces.[1-4,13-15]

Marginal bone loss around both titanium and zirconia implants remained within clinically acceptable thresholds. Meta-analytical data revealed no statistically significant differences in marginal bone loss between the two materials in short- and medium-term follow-ups, suggesting comparable peri-implant bone stability when appropriate clinical protocols were applied.[14-25]

Implant surface modifications, including changes in macrogeometry, microtopography, and chemical composition, were associated with improved early healing and biomechanical performance. However, long-term outcomes appeared to be more strongly influenced by patient-related and site-specific factors than by surface modifications alone.[6-9]

Immediate and early loading protocols demonstrated survival and success rates comparable to those of conventional delayed loading when strict clinical criteria were respected, such as adequate insertion torque, favorable bone quality, and controlled occlusal loading. These protocols were also associated with reduced treatment time and improved patient-reported outcomes.[10-12]

From a biological and esthetic perspective, zirconia implants showed favorable soft-tissue responses, with some studies reporting reduced bacterial adhesion and improved peri-implant tissue health. Esthetic outcomes were consistently superior for zirconia implants in anterior regions, whereas titanium implants demonstrated greater mechanical reliability in posterior, high-load situations.[9,13-17]

Discussion

The findings of this systematic synthesis confirm that titanium implants remain the gold standard in implant dentistry, supported by decades of robust clinical evidence and predictable long-term outcomes. The consistently high survival rates reported across multiple systematic reviews reinforce the reliability of titanium-based systems when osseointegration principles are strictly followed.[1-5]

The growing use of zirconia implants reflects an increasing demand for metal-free and esthetically optimized rehabilitation. The comparable survival rates reported in recent systematic reviews and randomized clinical trials support the clinical viability of zirconia implants, particularly in esthetically demanding anterior regions.[13-17] However, the higher incidence of early mechanical complications in specific zirconia implant designs highlights the importance of careful case selection and biomechanical planning.

Osseointegration remains a dynamic biological process influenced by implant material, surface characteristics, surgical technique, and host response. While surface modifications have demonstrated benefits in early bone healing, the literature consistently indicates that long-term implant success is primarily determined by patient-related and site-specific factors rather than surface technology alone. This finding underscores the need for individualized treatment planning rather than reliance on material innovations in isolation.

The favorable outcomes associated with immediate and early loading protocols reflect advancements in implant design and surface technology. Nonetheless, the evidence clearly demonstrates that these protocols should be applied selectively, as insufficient primary stability or inadequate occlusal control may compromise osseointegration and long-term success.

From a biological standpoint, zirconia implants may offer advantages related to soft-tissue integration and reduced bacterial adhesion, potentially contributing to improved peri-implant health. Esthetically, zirconia implants provide superior outcomes in visible regions due to their tooth-like color and reduced risk of mucosal discoloration. However, titanium implants continue to outperform zirconia in terms of mechanical strength, particularly in posterior regions subjected to high occlusal loads.

In summary, the current evidence supports zirconia implants as a viable alternative to titanium in selected clinical scenarios, especially when esthetic demands are paramount. Nevertheless, the limited availability of long-term randomized controlled trials necessitates further high-quality research to fully elucidate the biological stability, mechanical behavior, and complication profiles of zirconia implants under diverse clinical conditions.

Conclusion

This systematic review confirms that titanium implants remain the gold standard in implant dentistry, supported by extensive long-term evidence, predictable osseointegration, and superior mechanical reliability. Implant success is determined by a multifactorial interaction between biological principles, implant design, surface characteristics, loading protocols, and patient- and site-related factors. Zirconia implants have emerged as a viable metal-free alternative, particularly in esthetically demanding regions. Current evidence indicates that zirconia implants can achieve survival rates and marginal bone stability comparable to titanium implants in short- and medium-term follow-ups, while offering favorable soft-tissue responses and improved esthetic outcomes. However, mechanical limitations, especially in narrow-diameter and two-piece designs, remain a relevant concern. Advances in implant design and surface technology have enabled the successful application of immediate and early loading protocols, provided that strict clinical criteria are respected. Overall, zirconia implants represent a valid option in selected clinical situations, but further long-term randomized controlled trials are required to establish their biological and mechanical predictability under diverse clinical conditions.

Funding

This study was supported by the São Paulo Research Foundation (FAPESP), grant numbers 2019/24903-6, 2021/11499-2, and 2026/00967-9.

Acknowledgments

None

Conflict of interest

The authors declare that there are no conflicts of interest.

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Citation: Matos JDM, Batista JPO, Santos IP, et al. Titanium and zirconia dental implants: biological principles and clinical outcomes. *J Dent Health Oral Disord Ther.* 2026;17(2):74–78. DOI: 10.15406/jdhodt.2026.17.00673