RESEARCH PAPER

Zirconia vs Titanium Dental Implants: A Biomechanical and Clinical Perspective

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ABSTRACT

Background Titanium has defined implant dentistry since Brånemark first documented osseointegration in the 1960s, accumulating a long-term evidence base that few biomaterials can match.[1] Yet its metallic nature — with attendant aesthetic limitations, corrosion-related ion release, and unsuitability for metal-allergic patients — has driven clinicians and patients alike toward zirconia as a compelling ceramic alternative. Introduced to the implant market in the early 2000s, zirconia (yttria-stabilized tetragonal zirconia polycrystal, 3Y-TZP) offers tooth-colored esthetics, chemical inertness, and reduced bacterial adhesion characteristics, but its long-term mechanical reliability under clinical loading conditions remains a subject of active investigation.[2,4,5]

Objective To synthesize and critically appraise the biomechanical properties, osseointegration potential, peri-implant tissue responses, survival and success rates, failure modes, and evidence-based clinical selection criteria for zirconia and titanium dental implants, drawing from randomized controlled trials, systematic reviews, meta-analyses, and prospective cohort studies published through March 2025.

Methods A structured narrative review was conducted through comprehensive searches of PubMed/MEDLINE, Scopus, Web of Science, EMBASE, and the Cochrane Database. Risk of bias was assessed using AMSTAR-2 for systematic reviews and the Cochrane RoB2 tool for randomized controlled trials. Evidence certainty was evaluated using the GRADE framework.

Results Titanium implants demonstrate a benchmark 10-year cumulative survival of 98.8% and success rate of 97.0%.[2] Zirconia achieves comparable short-term survival at 12 months ($P = 0.0938$, no significant difference)[4] and a 10-year cumulative survival rate of 95.1% in appropriately selected systems.[5] However, one-piece zirconia implants supporting multi-unit prostheses demonstrate as low as 66.67% survival at 5 years, with peri-implantitis and tetragonal-to-monoclinic phase transformation identified as primary failure drivers.[7] The relative risk of survival significantly favoured titanium in RCT-level meta-analysis ($RR = 0.87$; 95% CI [0.78–0.98]; $P = 0.030$; $I^2 = 0\%$).[6] Titanium ion particles were detected at 40% of peri-implantitis biopsy sites, implicating a corrosion-driven inflammatory loop.[14] Marginal bone loss was significantly lower around titanium implants in one meta-analysis ($P = 0.001$; $I^2 = 0\%$).[9] Zirconia's advantages in esthetics, bacterial adhesion, and metal-allergy suitability are unambiguous but require careful patient and design selection.

Conclusions Neither material holds universal clinical superiority. Titanium remains the evidence-based default for posterior load-bearing regions, parafunctional patients, and medically compromised individuals.[2,5,11] Zirconia is the material of choice in high-aesthetic anterior zones and for metal-sensitive patients, provided implant design, surface treatment, and occlusal protocols are rigorously observed.[4,13,19] The choice is patient-specific and context-driven, not ideological.

Keywords: Dental implants, Zirconia, Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP), Titanium, Osseointegration, Biomechanics, Marginal bone loss, Peri-implantitis, Fracture resistance, Implant survival, Metal-free implants, Clinical outcomes

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1. INTRODUCTION

In 1965, Per-Ingvar Brånemark placed the first titanium dental implant in a human patient.[1] That implant remained in function for forty years. It was not coincidence — it was the beginning of a carefully observed phenomenon that Brånemark would call osseointegration, and it set titanium on a trajectory to become one of the most trusted biomaterials in medicine. For most of the decades that followed, the conversation in implant dentistry was not about what material to use, but how to use it better: surface roughness, implant geometry, loading protocols, platform switching, and prosthetic design.

That conversation changed when patients started asking different questions. Not just 'Will this implant last?' but 'Will people see metal through my gums in ten years?' Not just 'Is it biocompatible?' but 'Does it contain metals I might react to?' The rise of metal-free dentistry, growing awareness of titanium particle release in peri-implant tissues — documented at 40% of biopsy sites adjacent to peri-implant disease — and the aesthetic expectations of contemporary patients created a clinical demand that titanium, regardless of its mechanical excellence, could not fully satisfy.[14]

Zirconia stepped into this space. First established on the implant market in the early 2000s, yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) offered a compelling profile: tooth-colored, biologically inert, resistant to bacterial colonization, and mechanically robust enough — in vitro at least — to survive oral loading.[12,13] What followed was a body of research that has grown rapidly but unevenly, producing results that are simultaneously encouraging and cautionary.

The clinical reality in 2025 is that both materials are in widespread use, and the conversation has moved beyond the simplistic framing of 'zirconia versus titanium'. What clinicians need is a nuanced, data-driven comparison that supports individualized decisions — not a marketing position. This review was written with exactly that purpose. It examines the biomechanical properties of both materials with specificity, surveys the clinical evidence without cherry-picking favorable outcomes, and offers a practical decision framework grounded in what the peer-reviewed literature actually supports.[3,4,5,6,7,8,9]

2. BIOMECHANICAL PROPERTIES: WHAT THE PHYSICS TELLS US

2.1 Elastic Modulus and Stress Shielding

The elastic modulus of a material determines how much it deforms under a given load. Cortical bone has an elastic modulus of approximately 17–25 GPa.[15] Commercially pure titanium (cp-Ti) has a modulus of 100–110 GPa, while Ti-6Al-4V alloy sits at approximately 114 GPa.[12] Zirconia (3Y-TZP) is stiffer still, with moduli of 150–200 GPa.[12,19] Both materials are therefore substantially stiffer than the bone they anchor into.

When a material bears load on behalf of surrounding bone rather than transferring it through the tissue, the bone experiences less mechanical stimulus than it needs to remain healthy. This stress-shielding phenomenon activates osteoclast-mediated resorption and contributes to marginal bone loss over time.[15] Beta-titanium alloys such as titanium-niobium (TNTZ) are being actively developed to lower the effective elastic modulus closer to bone.[23] Zirconia's higher modulus may paradoxically amplify stress-shielding concerns — a finding finite element analysis (FEA) studies have begun to document, though clinical studies have not yet translated this into consistently divergent bone loss outcomes.[15]

2.2 Flexural Strength and Fracture Toughness

Flexural strength and fracture toughness are two different — and critically important — measures of how a material handles load. Flexural strength describes the maximum load before permanent deformation or fracture; fracture toughness (KIc) describes resistance to crack propagation once a crack has initiated. A material can be strong but brittle.[12]

Zirconia is precisely this kind of material. Its flexural strength of 900–1,200 MPa appears formidable on paper, but its fracture toughness of 5–10 MPa·m½ is dramatically lower than titanium's 55–115 MPa·m½.[12,19] The implications for clinical practice are substantial. Titanium — particularly Ti-6Al-4V — can absorb dynamic off-axis loading through plastic deformation before catastrophic failure. Zirconia cannot: once a crack initiates, propagation is rapid and irreversible.[5]

In vitro studies confirm that zirconia implants can endure 10 million masticatory cycles at 95 N force, but the bending moment to fracture (BMF) of zirconia implants was significantly lower than that of titanium equivalents.[19] The clinical translation is stark: zirconia is susceptible to fracture under off-axis and cyclic high-magnitude loading, particularly in narrow-diameter designs and posterior regions where occlusal forces regularly exceed 400–800 N.[5,12] Roehling et al. captured 26 fracture failures in their meta-analysis of 4,017 zirconia implants — the majority in narrow-diameter designs — confirming that implant geometry is an independent risk modifier for zirconia fracture.[5] Zirconia abutment preparation using rotary instruments carries an additional fracture risk through crack initiation at machined areas, which is why most contemporary one-piece zirconia systems are intentionally designed to avoid post-placement coronal adjustment.[15]

2.3 The Tetragonal-to-Monoclinic Transformation: Zirconia's Hidden Vulnerability

Pure zirconia is not dimensionally stable across the temperature and hydration ranges encountered clinically. Its transformation from tetragonal to monoclinic phase — driven by hydrothermal degradation, mechanical stress, and prolonged aqueous exposure — leads to a 3–5% volume expansion that generates internal micro-cracking and surface deterioration, a process known as low-temperature degradation (LTD) or 'aging'.[19] Crystallographic analyses of explanted zirconia implants from the Kohal et al. (2025) cohort revealed increased tetragonal-to-monoclinic (t→m) transformation on removed specimens, directly implicating this degradation pathway in late clinical failures.[7] The addition of yttria stabilizer (3–8 mol%) in 3Y-TZP suppresses but does not eliminate this transformation; alumina-toughened zirconia (ATZ) — incorporating 20 wt% alumina — demonstrates improved resistance to LTD and is increasingly used in contemporary ceramic implant systems.[8,19]

2.4 Titanium Corrosion and Ion Release: The Case Against Complacency

Titanium's biocompatibility rests on the self-passivating titanium dioxide (TiO_2) layer that forms almost instantaneously upon exposure to oxygen.[16] This layer is highly stable under most physiological conditions — but under low pH associated with peri-implant inflammation, fluoride-containing oral hygiene products, and fretting at the implant-abutment interface, it can be compromised, triggering corrosion and the release of titanium particles and ions into surrounding tissues.[16,17]

A 2024 investigation published in the International Journal of Oral Science documented dissolved titanium at 40% of biopsy sites adjacent to peri-implant disease, implicating a pathogenic feedback loop: titanium particles stimulate macrophage activation and cytokine release (TNF-α, IL-1β), which promotes bone resorption and tissue breakdown, which deepens pockets, creating more acidic conditions that further accelerate corrosion.[14] Simulated inflammatory and infectious environments significantly increase corrosion rates in titanium specimens, consistent with this self-amplifying mechanism.[17] The prevalence of titanium sensitivity in the general population is estimated below 0.6%, but the documented accumulation of titanium particles in peri-implant soft tissues raises legitimate concerns about subclinical inflammatory responses that existing protocols may not adequately detect.[14,17]

Zirconia avoids this concern entirely. Its chemical inertness means no ion release, no corrosion pathway, and no contribution to macrophage-mediated inflammatory cycles through metallic debris — a non-trivial clinical advantage for patients with metal sensitivities or existing peri-implant disease.

3. OSSEOINTEGRATION: BONE-TO-IMPLANT CONTACT AND HEALING DYNAMICS

3.1 The Titanium Standard

The sequence of woven bone formation followed by lamellar and parallel-fibered bone remodeling was first described around titanium implants and has been most thoroughly optimized for this material.[11] Surface treatment is the most powerful modifiable determinant of osseointegration speed and quality. Sandblasting followed by acid-etching (SLA) remains the technique of reference, creating a micro-rough topography (Ra 1.5–2.0 μm) that maximizes osteoblast attachment, protein adsorption, and bone-to-implant contact (BIC).[11,24] Hydrophilic modifications of SLA surfaces (modSLA/SLActive) further accelerate early osseointegration by maintaining surface energy and reducing the initial hydrophobic barrier

— effects documented in both animal and human histomorphometric studies.[11,24]

3.2 Zirconia Osseointegration: Surface-Dependent and Comparable When Optimized

Zirconia surfaces respond differently to conventional SLA protocols than titanium and require tailored treatment strategies. Sandblasting with alumina particles followed by acid-etching produces the ZLA (zirconia large-grit sandblasted and acid-etched) surface, which has demonstrated BIC values comparable to SLA titanium in controlled animal experiments.[11] Removal torque testing of acid-etched zirconia implants yielded values similar to sandblasted and acid-etched titanium implants, and histomorphometric analyses confirmed no significant difference in peri-implant bone density or BIC between optimally surface-treated zirconia and titanium implants.[11,16]

The critical qualifier is 'optimally surface-treated'. Machined (turned) zirconia surfaces produce substantially inferior osseointegration compared to treated surfaces — a gap that is larger than the equivalent difference in titanium systems.[5,16] Histological examinations of explanted zirconia implants from the Kohal et al. series confirmed that osseointegration was not the primary mechanism of failure in most cases — implants had integrated — rather, peri-implant disease progression drove the failures.[7] This underscores that biologic environment management and biofilm control after osseointegration are as important as initial BIC achievement.

3.3 Soft Tissue Integration and Bacterial Adhesion

Both titanium and zirconia can support hemidesmosomes and junctional epithelial attachment, but biofilm formation characteristics differ meaningfully between the materials.[13] Zirconia's higher surface electronegativity and inherent smoothness reduce initial adhesion of key periodontopathic species, including Porphyromonas gingivalis and Streptococcus mutans, compared to titanium surfaces of equivalent roughness.[6,13] Preclinical studies have documented higher microorganism counts on titanium surfaces relative to zirconia of comparable roughness.[6]

The clinical translation of this in vitro advantage remains ambiguous. Comparative trials have not consistently demonstrated significantly different plaque index values between zirconia and titanium implants in compliant patients under structured maintenance protocols[3,6] — emphasizing that patient hygiene behavior and professional recall take precedence over material-specific bacterial adhesion characteristics. However, in patients with suboptimal plaque control or systemic immunocompromise, theoretically lower zirconia biofilm burden may offer a meaningful, if currently underquantified, protective effect.

Table 1. Comparative Biomaterial Properties of Titanium and Zirconia Dental Implants

Property	Titanium (cp-Ti / Ti-6Al-4V)	Zirconia (3Y-TZP / ATZ)
Elastic Modulus	100–110 GPa (cp-Ti); 114 GPa (Ti-6Al-4V)	150–200 GPa (3Y-TZP)
Flexural Strength	300–600 MPa (cp-Ti); ~950 MPa (Ti-6Al-4V)	900–1,200 MPa (3Y-TZP)
Fracture Toughness (KIc)	55–115 MPa·m½ — superior ductility	5–10 MPa·m½ — brittle, low crack tolerance
Hardness (Vickers)	300–400 HV	1,200–1,400 HV
Corrosion Resistance	Passive TiO_2 layer; Ti-ion release documented at 40% of peri-implantitis biopsy sites	Chemically inert ceramic; negligible ion release; stable across oral pH range
Biocompatibility	Excellent; documented hypersensitivity <0.6%	Excellent; no metallic ion release; metal-allergy safe
Osseointegration (BIC%)	65–80% BIC with SLA; gold standard reference	Comparable BIC with ZLA surface treatment; similar removal torque to SLA-Ti in animal studies
Bacterial Adhesion	Higher adhesion on roughened SLA surfaces	Lower initial adhesion due to electronegativit

Property	Titanium (cp-Ti / Ti-6Al-4V)	Zirconia (3Y-TZP / ATZ)
	vs. smooth Zr in vitro	y; reduced in vitro biofilm
Esthetics	Gray metallic — mucosal discoloration risk in thin gingival biotype	Tooth-colored — no gray show-through regardless of tissue thickness
Implant Design Options	One- and two-piece; wide diameter/length range; well-documented macrogeometries	Predominantly one-piece; two-piece systems emerging; prosthetic flexibility limited
Stress-Shielding Risk	Elastic modulus mismatch with cortical bone (~17 GPa) promotes resorption	Higher modulus than Ti; ceramic brittleness limits FEA interpretation
Manufacturing	Established CNC machining; lower cost per unit	CAD/CAM milling required; higher cost; crack risk during abutment preparation

cp-Ti = commercially pure titanium; Ti-6Al-4V = titanium-aluminum-vanadium alloy; 3Y-TZP = 3 mol% yttria-stabilized tetragonal zirconia polycrystal; ATZ = alumina-toughened zirconia; BIC = bone-to-implant contact; SLA = sandblasted and acid-etched; ZLA = zirconia large-grit sandblasted and acid-etched; KIc = critical stress intensity factor (fracture toughness); HV = Vickers hardness; FEA = finite element analysis. Data synthesised from references [2,5,6,7,8,11,12,14,15,19].

4. CLINICAL OUTCOMES: SURVIVAL, SUCCESS, AND FAILURE MODES

4.1 Short-Term Survival: Where the Evidence Converges

At twelve-month follow-up, clinical evidence consistently shows no statistically significant survival difference between zirconia and titanium implants. The PROSPERO-registered systematic review by Padhye et al., encompassing two eligible RCTs and produced by the Centre for Oral Clinical Research at Queen Mary University of London, found a non-significant difference (P = 0.0938).[4] The 2024 meta-analysis by Morena et al., analyzing six RCTs comprising 152 patients and 448 implants (267 zirconia, 181 titanium), found no significant differences in bleeding on probing, plaque index, or pink esthetic score at one year.[3] These short-term findings have tempted some clinicians to conclude the two materials are equivalent — a conclusion that is premature, because short-term survival does not capture the mechanical and biological vulnerabilities that manifest over longer periods.

4.2 Medium and Long-Term Survival: Where the Evidence Diverges

When follow-up extends beyond two years, zirconia implant data become more heterogeneous and, in some systems, considerably less reassuring. The most comprehensive long-term analysis — Roehling et al. (Clinical Oral Implants Research, 2023), a meta-analysis of 25 studies encompassing 4,017 implants followed for up to 132 months — estimated a 10-year cumulative survival rate (CSR) of 95.1%.[5] However, 26 of 172 total failures were attributable to implant fracture (majority in narrow-diameter implants); drill preparation of the coronal part significantly reduced survival (P < 0.001); and discontinued market systems showed markedly lower survival than currently available ones.[5] This last finding is particularly sobering — some zirconia systems reached the market without adequate long-term validation, and patients who received those systems bear the clinical consequences.

The prospective case series by Kohal et al. (Clinical Oral Implants Research, 2025) reported a 5-year survival rate of just 66.67% for one-piece 3Y-TZP implants supporting three-unit fixed dental prostheses in 27 patients.[7] Mean marginal bone loss was 1.89 mm. Peri-implantitis was the dominant failure mechanism, and crystallographic analyses of explanted specimens confirmed tetragonal-to-monoclinic zirconia transformation — establishing material degradation as a contributing factor in clinical failure.[7]

The meta-analysis by Duan et al. provides perhaps the starkest comparative datapoint: 24 zirconia implants failed versus 11 titanium implants in included RCTs, with osseointegration failure accounting for 18 of the 24 zirconia losses.[6] The relative risk of survival was 0.87 favouring titanium (95% CI [0.78–0.98]; P = 0.030; $I^2 = 0\%$).[6] These numbers are clinically meaningful.

Titanium's benchmark remains the retrospective cohort by Buser et al.: 98.8% 10-year survival and 97.0% success rate across 511 SLA-surface implants in 303 partially edentulous patients, with a peri-implantitis prevalence of only 1.8% over the decade.[2] At 20 years, titanium implant survival data of approximately 75% have been reported for early systems, with contemporary SLA-surface designs expected to perform considerably better.[23]

4.3 Marginal Bone Loss: The Radiographic Proxy for Long-Term Health

The accepted criterion for successful implant function is marginal bone loss (MBL) not exceeding 1.5–2 mm in the first year, followed by annual losses below 0.2 mm.[11] For titanium implants, this threshold is well-documented as achievable in healthy, compliant patients. For zirconia implants, MBL data are more variable: Mohseni et al. reported MBL ranging from 0.63 to 2.06 mm across different observation periods up to 132 months.[8] The meta-analysis by da Hora Sales et al. found MBL to be significantly lower around titanium implants ($P = 0.001$; $I^2 = 0\%$), representing one of the clearest areas of material-specific advantage for titanium in the existing literature.[9]

4.4 Peri-Implant Disease: Different Risks, Shared Consequences

Peri-implantitis — progressive, infection-driven bone loss around osseointegrated implants — affects an estimated 14–22% of implants over ten-year periods and represents the most threatening long-term implant complication.[11] Both materials are susceptible, but through subtly different mechanistic pathways. Around titanium implants, the corrosion-inflammation feedback loop — in which titanium particle release stimulates macrophage cytokine production that promotes bone resorption — adds a uniquely material-specific dimension to peri-implant disease.[14,17] Around zirconia implants, peri-implantitis follows more conventional biofilm-driven pathways but is complicated by the challenge of treatment: mechanical debridement, implantoplasty, and laser-assisted decontamination approaches optimized for titanium may damage ceramic surfaces and paradoxically worsen subsequent biofilm accumulation.[7,19]

Table 2. Key Clinical Studies — Survival and Outcome Data (Vancouver References)

Author (Year) [Ref]	Study Design	Implants (Zr/Ti)	Follow-up	Survival Rate	Key Finding
Morena et al. (2024) [3]	SR & Meta-Analysis (RCTs)	267 Zr / 181 Ti	1 year	No sig. diff.	No significant difference in BOP, PI, or PES at 1 year; RoB2 assessed
Padhye et al. (2023) [4]	SR & Meta-Analysis	2 eligible RCTs	12 months	P = 0.0938 (NS)	Short-term survival comparable; Zr preferred in aesthetic zone when outcomes equivalent
Duan et al. (2023) [6]	SR & Meta-Analysis (RCTs)	Multiple RCTs	Variable	RR = 0.87 (p=0.030)	24 Zr vs 11 Ti failures; 18/24 Zr losses from osseointegration failure; $I^2 = 0\%$
Roehling et al. (2023) [5]	SR & Meta-Analysis	25 studies; 4,017 implants	Up to 132 months	10-yr CSR = 95.1%	172 failures; 26 fractures (mainly narrow-diameter); drill preparati

Author (Year) [Ref]	Study Design	Implants (Zr/Ti)	Follow-up	Survival Rate	Key Finding
					on significantly reduced survival ($p<0.001$)
Kohal et al. (2025) [7]	Prospective Case Series	54 Zr one-piece	5 years	66.67 %	MBL = 1.89 mm; peri-implantitis primary cause; t→m Zr transformation confirmed on explant crystallography
da Hora Sales et al. (2023) [9]	SR & Meta-Analysis	105 Zr / 87 Ti	Variable	Ti 87.4 % / Zr 78.1 % ($P=0.70$)	MBL significantly lower around Ti ($P=0.001$; $I^2=0\%$); PES and BOP not significantly different
Buser et al. (2012) [2]	Retrospective Cohort	511 Ti (SLA)	10 years	98.8 % survival; 97.0 % success	Peri-implantitis prevalence 1.8% over 10 years; Ti gold standard benchmark
Mohseni et al. (2024) [8]	SR & Meta-Analysis	2,083 pts; 4,017 implants	Up to 132 months	MBL 0.63–2.06 mm	Two-piece Zr lower survival vs one-piece ($p=0.017$); discontinued systems: lower survival ($p<0.001$)

SR = systematic review; RCT = randomized controlled trial; Zr = zirconia; Ti = titanium; BOP = bleeding on probing; PI = plaque index; PES = pink esthetic score; MBL = marginal bone loss; NS = not significant; CSR = cumulative survival rate; BIC = bone-to-implant contact; RR = relative risk; CI = confidence interval.

5. ESTHETICS AND PATIENT-CENTERED OUTCOMES

5.1 The Gray Problem and Why It Matters Clinically

The single most visible limitation of titanium implants in the anterior region is the risk of mucosal discoloration. Titanium's gray metallic body can transmit through overlying mucosa — particularly in patients with thin gingival phenotypes (biotype I or II, tissue thickness <2 mm) — creating a perceptible gray-blue tint visible in natural light at conversational distances.[12] A 5-year cumulative aesthetic complication rate for titanium implants in the anterior region has been described, with gingival discoloration as the predominant aesthetic failure mode.[5] For patients who present specifically to replace a visible anterior tooth, a perceptible color artifact constitutes treatment failure in their own assessment, regardless of what probing depths and bone levels indicate. Zirconia eliminates this risk. Its white-ivory coloration, combined with its light-transmissive properties, produces natural tissue color that does not change with gingival recession or mucosal thinning over time.[13,19] The pink esthetic score (PES) and white esthetic score (WES) have demonstrated comparable or superior scores for zirconia implants in the anterior zone relative to titanium in multiple prospective investigations.[3,4] Morena et al.'s 2024 meta-analysis found no significant difference in PES between groups at one year, but with a directional trend favouring zirconia in aesthetically demanding sites.[3]

5.2 Patient-Reported Outcomes and Quality of Life

Beyond clinical parameters, how patients experience their implants matters. Oral health-related quality of life (OHRQoL) data for implant patients generally show high satisfaction across both materials.[18] However, patients with aesthetic concerns — specifically those who have noticed mucosal discoloration around titanium implants — report meaningfully lower satisfaction scores.[12] The growing movement toward patient-centered outcome reporting in implant research reflects awareness that clinical success metrics do not capture the full patient experience.

6. SPECIAL POPULATIONS AND MATERIAL-SPECIFIC CONSIDERATIONS

6.1 Metal Allergy and Titanium Sensitivity

Titanium allergy affects less than 0.6% of the general population, and genuine hypersensitivity reactions are even rarer.[12] However, emerging evidence of titanium particle accumulation in peri-implant soft tissue at 40% of peri-implantitis biopsy sites raises the possibility of subclinical inflammatory responses that current allergy testing protocols may not detect.[14] Patch testing for titanium allergy remains technically challenging and poorly standardized. For patients with documented metal sensitivities — particularly to nickel, cobalt, or chromium — zirconia implants represent the only implant option that eliminates metallic exposure entirely, supported by professional consensus statements though not yet by randomized trial data in specifically enrolled metal-sensitive populations.[13]

6.2 Systemic Disease Considerations

Controlled diabetes mellitus is an established risk factor for impaired osseointegration and increased peri-implant disease susceptibility around both titanium and zirconia implants.[17] Titanium surface modifications — including zinc oxide (ZnO) coatings, hydroxyapatite (HA) layers, and protein adsorption-enhancing treatments — have been studied specifically to mitigate impaired wound healing in diabetic models.[17] No equivalent body of disease-specific modification literature exists for zirconia, leaving clinicians without evidence-based guidance for optimizing outcomes in diabetic patients receiving ceramic implants. For osteoporotic patients receiving bisphosphonate or denosumab therapy, the risk of medication-related osteonecrosis of the jaw (MRONJ) applies to implant placement regardless of material.[11] Material choice should not drive decision-making in this population.

6.3 Pediatric and Young Adult Patients

Implant placement before completion of alveolar development risks infraocclusion as surrounding bone continues to grow.[11] Neither material has a documented advantage in this setting. For young adults seeking metal-free solutions, zirconia may offer a psychosocial benefit — a consideration that is not biomechanically quantifiable but is clinically real.

7. CLINICAL DECISION FRAMEWORK

The following framework synthesizes the evidence reviewed into actionable clinical guidance.[3,4,5,6,7,8,9,11,12,13,14,19] It is intended as a decision-support tool rather than a rigid algorithm — individual clinical judgment, patient preferences, operator experience, and specific anatomical and systemic factors must always take precedence over categorical rules.

Table 3. Scenario-Based Clinical Decision Framework — Material Selection Guide (Vancouver References)

Clinical Scenario	Titanium — Rationale	Zirconia — Rationale
Posterior load-bearing region	Preferred. KIc 55–115 MPa·m½ and 10-yr survival 97–98.8% [2]. Superior tolerance of off-axis occlusal forces.	Caution. Fracture risk in narrow-diameter designs; 26 fracture failures in Roehling meta-analysis [5].
High-aesthetic anterior zone	Acceptable. Risk of gray show-through in thin biotype; aesthetic complication risk after 5 years.	Preferred. Tooth-colored body eliminates mucosal discoloration; comparable short-term survival [4].

Clinical Scenario	Titanium — Rationale	Zirconia — Rationale
Metal-allergic / Ti-sensitive patient	Caution. Ti particle release at 40% of peri-implantitis sites [14]; hypersensitivity rare but documented.	Strongly preferred. Metal-free; no ionic release; no documented allergic reactions in published literature.
Thin gingival phenotype	Acceptable; requires soft-tissue management and possible grafting.	Preferred. Opaque ceramic eliminates gray discoloration regardless of tissue thickness.
Parafunctional habits (bruxism)	Preferred. Ductility of Ti-6Al-4V absorbs dynamic loading; lower catastrophic fracture risk.	Not recommended without occlusal splint. KIc 5–10 MPa·m½ carries brittle fracture risk under high cyclic forces [12].
Immediate implant placement	Well-documented; SLA/modSLA surfaces accelerate osseointegration in fresh sockets [11].	Emerging evidence; one-stage designs allow immediate provisionalization but require strict occlusal offloading.
Medically compromised / immunosuppressed	Preferred. Decades of safety data across systemic conditions; extensive complication literature.	Insufficient long-term evidence in compromised hosts; use with caution.
Controlled diabetes mellitus	Acceptable with HbA1c <7%. ZnO/HA surface coatings mitigate impaired osseointegration [17].	Limited disease-specific evidence; theoretical anti-inflammatory benefit unproven clinically.

Framework based on peer-reviewed evidence through March 2025. As the long-term evidence base for zirconia matures, recommendations may evolve. Clinicians are encouraged to enroll eligible patients in prospective registries where available.

8. FUTURE DIRECTIONS AND EMERGING TECHNOLOGIES

8.1 Surface Innovation in Both Materials

The most significant advances in titanium implant technology are occurring at the nanoscale. Nanostructured titanium dioxide surfaces, ion-implanted surfaces, and bioactive coatings incorporating calcium phosphate, silver nanoparticles, zinc ions, and peptide growth factors are being developed to accelerate osseointegration, reduce bacterial colonization, and enhance bone apposition rates.[17,24] For zirconia, nano-structuring has been explored as an alternative to sandblasting and etching — a preclinical sheep study demonstrated equivalent bone mineral change on nano-structured surfaces compared to the commercial ZLA control — potentially simplifying manufacturing and eliminating surface damage risks associated with alumina particle bombardment.[19]

8.2 The Titanium-Zirconium Alloy: A Bridge Material

Titanium-zirconium alloy (TiZr; Roxolid, Institut Straumann AG) — containing 13–17 wt% zirconium alloyed with titanium — achieves higher tensile strength than cp-Ti while maintaining comparable biocompatibility.[10] Its elastic modulus is similar to cp-Ti, avoiding the higher stress-shielding risk of pure zirconia, while enabling smaller diameters (3.3 mm) with adequate mechanical performance.[10] For patients requiring narrow-diameter implants where bone width is limited — precisely the scenario where pure zirconia fracture risk is highest — TiZr represents a biologically favourable and mechanically validated compromise.[5,10]

8.3 CAD/CAM Fabrication, 3D Printing, and Custom Zirconia Implants

Custom root-analog zirconia implants — designed from CBCT-derived bone anatomy and fabricated via CAD/CAM milling — offer the theoretical advantage of maximizing primary stability through precise anatomical fit.[15] A scoping review identified mechanical and biological benefits, though clinical validation through adequately powered prospective trials remains pending.[15]

Three-dimensional printing of titanium implants with controlled porosity is already in clinical use, enabling elastic moduli closer to bone and promoting vascular ingrowth within implant structures.[23] Extension of these manufacturing approaches to zirconia ceramics faces fundamental challenges — sintering shrinkage, crack propagation during layer deposition — that current research is actively working to resolve.[19]

8.4 Bioactive Coatings and Therapeutic Surfaces

The frontier of implant surface science is moving toward biological intelligence — surfaces that actively participate in the healing process. Zirconia surfaces functionalized with bioactive proteins, growth factors (BMP-2, VEGF), and antimicrobial peptides are being evaluated in preclinical models.[19] Titanium surfaces incorporating drug-eluting mechanisms — releasing local antibiotics, anti-inflammatory agents, or angiogenic peptides on demand — are similarly under development.[17,24] These technologies, if clinically validated, may eventually narrow the performance gap between titanium and zirconia significantly.

9. LIMITATIONS OF THE CURRENT EVIDENCE BASE

Any honest appraisal of this field must acknowledge its limitations. The volume of randomized controlled trial data directly comparing titanium and zirconia implants remains modest — the largest meta-analyses include fewer than ten eligible RCTs, constraining the statistical power of subgroup analyses.[3,4,6] Follow-up periods across most studies remain shorter than the decade or more that constitutes long-term implant evidence, and the heterogeneity of zirconia implant designs, surface treatments, and clinical protocols across studies makes cross-study comparisons challenging.[5,8]

The zirconia implant market itself has not been stable: numerous systems introduced over the past two decades have been subsequently discontinued, and data on discontinued systems may not represent the performance of contemporary commercially available implants.[5] Roehling et al.'s meta-analysis found that discontinued implants were associated with significantly lower survival ($P < 0.001$)[5] — underscoring the importance of distinguishing between implant generations and designs rather than treating 'zirconia implants' as a homogeneous category.

Publication bias must also be acknowledged.[3,6] Manufacturers who fund clinical trials have commercial interests that may — consciously or not — influence study design, participant selection, and publication timing. Negative results in implant trials are underrepresented in the published literature relative to their actual clinical frequency. Clinicians reading the literature should maintain healthy skepticism toward studies with small sample sizes, single-center designs, and short follow-up periods that report uniformly positive outcomes for either material.

10. CONCLUSIONS

The question 'Which is better — titanium or zirconia?' deserves the same answer most good clinical questions do: it depends. Both materials are capable of supporting successful implant therapy, and both carry specific risks and limitations that the other does not.[3,4,5,6,7,8,9]

Titanium holds genuine superiority in fracture toughness, long-term survival documentation, prosthetic versatility, and suitability for high-load posterior applications and medically complex patients.[2,5,11] Its drawbacks — aesthetic limitations in thin-biotype anterior sites, corrosion-related ion release in inflamed peri-implant environments, and unsuitability for metal-allergic individuals — are real but not universal clinical problems.[14,17]

Zirconia holds genuine superiority in esthetic outcomes in the anterior zone, biocompatibility for metal-sensitive patients, and the psychological reassurance of metal-free oral rehabilitation.[13,19] Its drawbacks — lower fracture toughness, vulnerability to late tetragonal-to-monoclinic degradation, more demanding surface treatment requirements, limited prosthetic design options, and a long-term evidence base that remains thinner and more heterogeneous than titanium's — are equally real.[5,7,8,12]

The practical conclusion is that these materials are not interchangeable defaults but complementary tools in a clinician's armamentarium. Selection should be driven by the specific patient's anatomy, loading conditions, gingival phenotype, aesthetic expectations, systemic health, and allergic history — not by institutional habit, laboratory marketing, or the enthusiasm of a weekend course.[3,11,13]

The clinician who understands both materials at the mechanistic level and knows when each is the right choice will serve patients better than one who has committed to either without reservation.

As the evidence base for zirconia implants continues to mature — particularly as long-term multicentre prospective studies accumulate — the field's capacity to make evidence-based recommendations will improve.[4,5,8] Until then, clinical judgment, patient-centered decision-making, and honest informed consent remain the most important instruments in this comparison.

Conflict of Interest Statement

The authors declare no financial or personal conflicts of interest. No funding was received from implant manufacturers or commercial entities for the conduct of this review.

Ethical Statement

This article is a narrative and systematic evidence synthesis. It does not involve primary patient data collection, human subjects research, or animal experimentation. Ethical approval was not required.

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