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LONG-TERM PERFORMANCE OF METAL-FREE ALTERNATIVES IN IMPLANT DENTISTRY: A CRITICAL REVIEW OF ZIRCONIA AND MODIFIED POLYETHERETHERKETONE (PEEK) IMPLANTS COMPARED WITH GRADE 4/5 TITANIUM

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ABSTRACT

Titanium (grade 4 commercially pure and grade 5 Ti-6Al-4V) alloys remain the benchmark fixture materials in implant dentistry on the strength of several decades of cohort and randomised evidence. Growing esthetic demand, concern over thin soft-tissue biotypes, and interest in metal-free rehabilitation have driven adoption of yttria-stabilised tetragonal zirconia polycrystal (Y-TZP) implants and, more recently, modified polyetheretherketone (PEEK) as alternative fixture and abutment materials. This review critically appraises the published evidence on the long-term (>10 year) clinical performance, fatigue strength and survival of zirconia and PEEK implants relative to grade 4/5 titanium. A narrative synthesis of systematic reviews, meta-analyses, randomised controlled trials (RCTs) and mechanical fatigue studies indexed in MEDLINE, Cochrane CENTRAL and Embase was undertaken. Zirconia implants demonstrate cumulative survival rates approaching those of titanium at 5-7 years (94-98%) and a pooled 10-year cumulative survival rate near 95%, together with consistently favourable pink-esthetic and soft-tissue outcomes, but fracture-driven failure, particularly of narrow-diameter one-piece designs, remains a distinguishing mechanical weakness. Direct RCT evidence comparing zirconia with titanium is limited to two to four trials with follow-up rarely exceeding 5-7 years. PEEK implants and PEEK-based abutments offer a low elastic modulus that reduces stress-shielding but show fatigue limits and fracture toughness inferior to titanium under ISO 14801 testing, and clinical fixture-level survival data beyond the short term are essentially absent. No RCT was identified that directly compares fatigue strength and long-term survival of zirconia or PEEK against grade 4/5 titanium implants over a 10-year horizon. Titanium therefore remains the material of choice for load-bearing and long-span indications, while zirconia is a reasonable metal-free option in esthetically demanding, lower-load sites pending longer-term randomised data; PEEK's clinical role remains provisional and adjunctive rather than as a definitive fixture material.

Keywords: Dental Implants; Zirconia; Polyetheretherketone (PEEK); Titanium; Fatigue Strength; Implant Survival

1 INTRODUCTION

Endosseous titanium implants have underpinned modern implant dentistry for more than four decades, owing to a combination of favourable corrosion resistance, biocompatibility, osseointegration potential and mechanical strength [1]. Commercially pure (cp) titanium grade 4 and the alpha-beta alloy grade 5 (Ti-6Al-4V, and its extra-low-interstitial variant Ti-6Al-4V ELI) remain the two most widely used fixture materials, with grade 5 offering substantially higher tensile and fatigue strength than grade 4 cp titanium at the cost of alloying elements (aluminium and vanadium) that have occasionally raised biocompatibility and hypersensitivity concerns [2].

Over the past fifteen years, patient demand for metal-free rehabilitation, concern over thin buccal soft-tissue biotypes revealing a grey titanium substructure, and reports of titanium hypersensitivity have driven interest in ceramic and polymeric alternatives [3,4]. Yttria-stabilised tetragonal zirconia polycrystal (Y-TZP, commonly termed "zirconia") implants were introduced as a tooth-coloured, allegedly bioinert alternative with reduced plaque affinity and favourable soft-tissue integration [1,2]. More recently, modified polyetheretherketone (PEEK) — a semicrystalline, radiolucent, high-performance thermoplastic with an elastic modulus closer to that of cortical bone than either titanium or zirconia — has been proposed for implant abutments, provisional restorations and, on a more limited basis, implant fixtures [5,6].

Both materials show genuine clinical promise. However, clinicians adopting them must weigh short- and medium-term esthetic and biological advantages against a comparatively immature long-term mechanical evidence base. Systematic reviews consistently note that, unlike titanium, zirconia and PEEK implants lack the extensive decade-plus randomised controlled trial (RCT) evidence needed to confirm equivalent fatigue strength and survival under functional load [3,7,8].

The objective of this review is therefore to critically synthesise the available literature on the long-term (>10 year) clinical performance, fatigue behaviour and survival of zirconia and modified PEEK implants, and to determine to what extent this evidence permits direct, randomised comparison with grade 4/5 titanium. The review addresses the hypothesis that, despite promising esthetic and soft-tissue data, metal-free alternatives currently lack sufficient long-term randomised comparative data on fatigue strength and survival to be considered interchangeable with titanium in load-bearing indications.

2 MATERIALS AND METHODS

This is a critical narrative review rather than a formal systematic review with meta-analysis; no new patient data were generated, and no ethical approval, institutional review board clearance or informed consent was required, in keeping with the design of a literature-based review article.

An electronic search of MEDLINE (PubMed), the Cochrane Central Register of Controlled Trials (CENTRAL) and Embase was performed for the period January 2005 to September 2026. Search terms combined "dental implant*", "zirconia" OR "zirconium oxide" OR "Y-TZP", "polyetheretherketone" OR "PEEK", "titanium" OR "grade 4" OR "grade 5" OR "Ti-6Al-4V", with "survival", "fatigue", "fracture", "randomised controlled trial" and "long-term". Reference lists of retrieved systematic reviews and meta-analyses were hand-searched for additional eligible studies (backward citation search).

Eligible sources comprised systematic reviews and meta-analyses, RCTs and prospective or retrospective cohort studies reporting implant survival, marginal bone loss, esthetic outcome or in vitro/ISO 14801 fatigue data for zirconia or PEEK implants, with or without a titanium comparator, and mechanical or clinical studies characterising grade 4 or grade 5 titanium fatigue strength or long-term survival. Case reports, studies with fewer than 15 implants (except where cited within a systematic review), and purely preclinical animal studies were excluded unless specifically discussing osseointegration mechanisms relevant to the discussion. Given the heterogeneity of implant designs, follow-up intervals and outcome definitions across the retrieved literature, a narrative rather than quantitative synthesis was undertaken, with pooled effect estimates reported only where directly quoted from the source meta-analyses.

3 RESULTS AND DISCUSSION

3.1 Titanium as the benchmark fixture material

Titanium remains the reference standard against which metal-free alternatives are judged. Fatigue testing of fractured commercially pure (cp) titanium grade 4 narrow dental implants against titanium alloyed with 15% zirconium (TiZr) and cold-worked grade 4 titanium confirms that unalloyed cp titanium grade 4 exhibits a comparatively low fatigue limit under cyclic tri-axial loading, whereas alloying or cold-working measurably raises the fatigue threshold and reduces the risk of long-term mechanical failure [9]. Grade 5 (Ti-6Al-4V/Ti-6Al-4V ELI) and TiZr alloys are therefore

generally preferred for narrow-diameter or high-load posterior applications, while grade 4 cp titanium is favoured where maximum biocompatibility and osseointegration potential are prioritised over peak mechanical strength [9].

This mechanical margin is reflected in an unusually mature long-term clinical record. In a retrospective cohort of 511 sandblasted, acid-etched (SLA) titanium implants followed for 10 years in 303 partially edentulous patients, Buser and colleagues reported a 10-year implant survival rate of 98.8% and a success rate of 97.0%, with no implant fractures recorded over the observation period [10]. A five-year double-blind, split-mouth RCT of small-diameter grade 4 titanium and TiZr alloy implants likewise reported cumulative survival of 97.8-98.9%, with the same cohort subsequently extended to a 10-year randomised core-trial follow-up [11]. This combination of decade-scale cohort data, randomised comparative trials and a very low reported fracture incidence constitutes the benchmark that zirconia and PEEK implants have yet to match.

3.2 Zirconia implant survival: pooled cohort evidence

Zirconia implant survival has been the subject of numerous systematic reviews, with pooled outcomes varying according to implant design (one-piece versus two-piece), whether the coronal portion was prepared by drilling, and continued market availability of the system studied. An early systematic review by Hashim and colleagues, based on 1 year of function, reported an overall survival rate of 92% (95% CI 87-95%), with substantial heterogeneity between studies, and concluded that the evidence was insufficient at that time to justify zirconia as an equivalent alternative to titanium [2]. A subsequent systematic review by Pieralli and colleagues, restricted to RCTs and prospective studies of more than 15 patients, calculated a 12-month survival rate of 95.6%, with an estimated annual decline thereafter of approximately 0.05% [1].

The most recent and comprehensive update, by Mohseni, Soufi and Chrcanovic, pooled 25 studies encompassing 4017 implants and 2083 patients, of which only seven studies had follow-up beyond 60 months. The pooled 10-year cumulative survival rate (CSR) was 95.1%, closely approaching titanium benchmarks; however, of 172 recorded failures, 26 were attributable to implant fracture (predominantly in narrow-diameter implants), and implants with a coronally drilled preparation and two-piece designs showed statistically significantly lower survival than non-prepared, one-piece implants ($p < 0.001$ and $p = 0.017$, respectively) [3]. A related meta-analysis by Roehling and colleagues reported broadly consistent short- and medium-term outcomes across zirconia systems [4]. Collectively, these data indicate that, at the level of pooled cohort and registry-style evidence, contemporary one-piece zirconia implants can approach titanium-level survival over a decade, but that design-dependent fracture risk remains a distinguishing mechanical limitation not shared to the same degree by titanium.

3.3 The randomised controlled trial gap for zirconia versus titanium

The critical evidentiary gap identified across the zirconia literature is the scarcity of RCTs directly comparing zirconia with titanium over long follow-up periods. A systematic review and meta-analysis by Padhye and colleagues, searching specifically for RCTs and controlled clinical trials, identified only two RCTs (in two distinct patient cohorts, 100 zirconia and 99 titanium implants) with follow-up ranging from 12 to 80 months; survival differences at 12 months were not statistically significant ($p = 0.0938$), but the authors explicitly concluded that "future RCTs are warranted to evaluate the long-term outcomes of zirconia implants" [5]. A parallel RCT-focused meta-analysis by Duan and colleagues similarly confirmed comparable short- to medium-term survival and peri-implant indices between zirconium and titanium implants, again drawing on a very limited randomised evidence base [6]. A broader systematic review of RCTs comparing titanium with titanium-zirconium or zirconia implants by Fernandes and colleagues reached the same conclusion regarding the paucity of long-term randomised comparative data [7].

More recent individual RCTs have begun to extend follow-up, though still well short of a decade. de Beus and colleagues reported a randomised trial of zirconia versus titanium implants in maxillary single-tooth replacement [8], and Ferrantino and colleagues published five-year outcomes of an RCT comparing zirconia and titanium abutments, again the longest follow-up identified within a randomised design for this comparison [12]. No RCT identified in this review extended fatigue-relevant, implant-level comparative follow-up to the 10-year horizon achieved by titanium cohort studies such as that of Buser and colleagues [10]. This asymmetry — pooled cohort CSR data approaching 95% at 10 years, set against RCT evidence capped at 5-7 years — represents the central limitation of the current zirconia evidence base and directly constrains any claim of long-term fatigue-strength equivalence with titanium.

3.4 Esthetic and soft-tissue outcomes

Esthetic and soft-tissue outcomes are where zirconia's comparative advantage is most consistently demonstrated. In the RCT by Padhye and colleagues, pink esthetic scores (PES) were higher for zirconia (10.33 ± 2.06 to 11.38 ± 0.92) than for titanium (8.14 ± 3.58 to 11.56 ± 1.0) [5]. A randomised trial comparing anodised titanium and zirconia abutments similarly found significantly lower colour difference (ΔE) values and higher PES for zirconia [13].

Comparative studies of peri-implant tissue health have reported reduced probing depth, reduced bleeding on probing and more favourable marginal bone preservation around zirconia relative to titanium abutments [14].

This picture is not entirely uniform, however. A within-subject histological comparison by van Brakel and colleagues found no statistically significant difference in vascular density or inflammation grading between peri-implant tissues adjacent to zirconia and titanium abutment surfaces at 3 months, suggesting that at the histological level the two materials elicit a broadly similar soft-tissue response despite the differing clinical and optical impressions reported elsewhere [15]. Taken together, the esthetic and optical advantages of zirconia — lower colour mismatch, higher PES, and the absence of a visible grey shadow through thin mucosa — are well supported, but claims of a categorically superior biological soft-tissue response should be interpreted cautiously given conflicting histological findings.

3.5 Fracture and fatigue behaviour of zirconia

Fracture, rather than osseointegration failure, is the dominant long-term mechanical concern for zirconia. The pooled analysis by Mohseni and colleagues attributed 26 of 172 recorded failures directly to implant fracture, occurring disproportionately in narrow-diameter, one-piece designs subjected to coronal preparation [3]. This is consistent with the intrinsically lower fracture toughness of Y-TZP ceramics relative to titanium alloys, and with zirconia's susceptibility to low-temperature degradation and subcritical crack growth under cyclic loading, phenomena that have no direct analogue in ductile titanium alloys. From a materials-science standpoint, this explains why zirconia survival curves, while approaching titanium at 10 years in aggregate, continue to show a small but persistent fracture-related tail of failures that titanium cohorts largely do not exhibit [3,10].

3.6 Mechanical and fatigue performance of modified PEEK

PEEK's principal mechanical rationale is its elastic modulus (approximately 3-4 GPa for unmodified PEEK, rising toward 18 GPa with carbon-fibre or ceramic reinforcement), which is far closer to that of cortical bone than titanium's approximately 110 GPa, theoretically reducing stress-shielding and the associated risk of marginal bone loss [17]. Finite-element and ISO 14801 fatigue testing, however, consistently identify a mechanical shortfall relative to titanium. Lee and colleagues, testing glass-fibre-reinforced PEEK against titanium under ISO 14801 protocols, characterised the fatigue limits of PEEK and confirmed reduced stress-shielding but a lower fatigue threshold than titanium implant systems [18]. Schwitalla and colleagues subsequently quantified fatigue limits across several PEEK formulations, again reporting values below those typically achieved by titanium under equivalent loading [19].

A recent finite-element comparison of carbon-fibre-reinforced PEEK (CF-PEEK) and titanium implants across variable bone-density models found that, while titanium components experienced higher von Mises stress under oblique loading, CF-PEEK abutment and screw components showed significantly higher strain and were more susceptible to fatigue failure, particularly in low-density trabecular bone [17]. A systematic review of PEEK implant abutments by Ghazal-Maghras and colleagues, evaluating dynamic fatigue, fracture toughness and loss of torque, concluded that available evidence does not yet demonstrate that PEEK abutments possess sufficient biomechanical properties to replace definitive titanium abutments, and characterised PEEK instead as an alternative or provisional material, particularly suited to lower-load anterior applications [20]. A broader systematic review of PEEK dental prostheses reached a similar conclusion regarding the current balance of mechanical and clinical evidence [16].

3.7 The clinical survival evidence gap for PEEK implants

Unlike zirconia, for which cohort survival data now extend to a pooled 10-year CSR, clinical fixture-level survival data for PEEK implants beyond the short-to-medium term are essentially absent from the peer-reviewed literature. A systematic review of clinical studies by Khurshid and colleagues, searching specifically for PEEK dental prostheses, concluded that there is presently insufficient evidence to ascertain the long-term survival of PEEK-based dental restorations of any kind [16]. The great majority of clinical PEEK studies address abutments, interim restorations, and removable prosthesis frameworks rather than the implant fixture itself, and no RCT directly comparing PEEK implant fixture survival or fatigue performance with grade 4/5 titanium over a multi-year horizon was identified in this review [16,20]. This represents a more pronounced evidentiary gap than that seen for zirconia: whereas zirconia lacks decade-scale RCT data but possesses substantial decade-scale cohort data, PEEK currently lacks robust clinical survival data of either kind beyond a handful of years, despite an increasingly detailed *in vitro* and finite-element mechanical characterisation.

3.8 Synthesis and clinical implications

Synthesising the preceding sections, three points bear directly on the review's objective. First, titanium's 10-year, and in places longer, cohort and RCT record — with fracture rates approaching zero [9,10,11] — remains unmatched in scale and duration by either alternative material. Second, zirconia has produced credible pooled cohort evidence of near-titanium 10-year survival (approximately 95%) alongside consistently favourable esthetic outcomes, but the RCT evidence directly comparing zirconia and titanium fatigue strength and survival remains confined to two to four trials

with a maximum follow-up in the 5-7 year range [3,5,6,7,8,12]. Third, PEEK's favourable elastic-modulus profile is well characterised mechanically, but its fatigue limits under ISO 14801 testing are measurably lower than titanium's, and clinical fixture-level survival evidence of any duration — randomised or otherwise — remains sparse [16,17,18,19,20].

For the practising clinician, this evidence pattern supports a cautious, site- and case-specific approach: titanium (grade 5 or TiZr alloys where higher fatigue strength is required, grade 4 cp titanium where biocompatibility is prioritised) remains the appropriate default for load-bearing and long-span posterior indications; zirconia represents a reasonable metal-free option in esthetically demanding, lower-load anterior sites, with the proviso that its fracture-related failure mode should be discussed as part of informed consent; and PEEK, at present, is best regarded as an adjunctive or provisional material rather than a validated long-term fixture alternative to titanium.

4 CONCLUSION

Grade 4 and grade 5 titanium continue to represent the mechanically and clinically best-documented implant fixture materials, supported by decade-plus cohort studies and RCTs demonstrating survival rates consistently above 95% and negligible fracture incidence. Zirconia implants have narrowed this gap considerably, with pooled 10-year cumulative survival rates near 95% and consistently superior esthetic and pink-tissue outcomes, but fracture remains a distinguishing failure mode and direct randomised comparisons with titanium remain limited to short- and medium-term follow-up. Modified PEEK offers a biomechanically attractive low-modulus profile that may reduce stress-shielding, yet its fatigue strength under standardised testing is inferior to titanium, and long-term clinical fixture-level survival data, randomised or otherwise, are presently lacking. No study identified in this review provides direct, long-term (>10 year) randomised comparative data on fatigue strength and survival between either metal-free alternative and grade 4/5 titanium. Well-designed, adequately powered RCTs with fatigue-related mechanical failure as a defined long-term endpoint are required before zirconia or PEEK implants can be considered evidence-based substitutes for titanium in load-bearing implant dentistry.

STATEMENTS ON COMPLIANCE WITH ETHICAL STANDARDS

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