En ligne
https://www.atrss.dz/ajhs

Review

Clinical Performance of Titanium versus Zirconia Dental Implants: A Systematic Review of Clinical Trials

Performance clinique des implants dentaires en titane par rapport à ceux en zircone : une revue systématique des essais cliniques

Hakima HOUARI BELKADI [1,2], Linda AMROUN [1,2], Abdelwaheb CHEHAME [1,2], Soumia BOUMEDIENNE [1,2], Ali BOUHEKA [1,2], Fatima Zohra HOUARI [3]. Souad BENAOUF [1,2].

[1] Department of Dentistry, Faculty of Medicine, Dental Technology & Biomaterials Research Laboratory, University of Oran 1, Oran, Algeria
[2] Department of Dentistry, Faculty of Medicine, Dental Technology & Biomaterials Research Laboratory, University of Oran 1, Oran, Algeria
[3] National School of Agronomy of Mostaganem, Mostaganem, Algeria

ABSTRACT

Introduction: Titanium implants are generally regarded as the reference standard in oral implantology because of their well-documented long-term performance and high biocompatibility. However, increasing esthetic demands and the growing interest in metal-free treatment options have led to the development of zirconia implants. This systematic review aimed to analyze and compare the clinical outcomes of zirconia and titanium implants based on evidence derived from clinical trials.
Materials and Methods: A systematic literature search was performed in the PubMed database in accordance with PRISMA guidelines, with no restriction on publication date. Only prospective and randomized clinical trials conducted in humans that allowed a comparison of titanium and zirconia implants. Twelve studies met the inclusion criteria. The evaluated outcomes included implant survival rate, marginal bone loss, peri-implant tissue response, biological and mechanical complications, and patient-reported outcomes.
Results: Implant survival rates were high for both materials, ranging from 88.8% to 100%, with no relevant differences reported in short- to medium-term follow-up. Marginal bone loss and soft tissue responses were generally comparable between groups. Biological complications were infrequent and showed no clear differences. However, zirconia implants demonstrated a higher tendency toward mechanical complications, particularly fractures in one-piece designs. A slight aesthetic advantage was frequently reported in favor of zirconia.
Conclusion: Zirconia implants seem to represent a reliable alternative to titanium implants in specific clinical situations, showing similar short- to medium-term outcomes. Nevertheless, their mechanical limitations and the lack of long-term evidence remain important concerns. Further well-designed randomized clinical trials with extended follow-up are still required.

KEYWORDS: Dental implants, Titanium, Zirconia, Osseointegration, Clinical outcomes.

RESUME

Introduction : Les implants en titane sont généralement considérés comme la référence en implantologie orale, en raison de leurs performances à long terme bien documentées et de leur excellente biocompatibilité. Toutefois, l'augmentation des exigences esthétiques et l'intérêt croissant pour les options thérapeutiques sans métal ont favorisé le développement des implants en zircone. Cette revue systématique avait pour objectif d'analyser et de comparer les

résultats cliniques des implants en zircone et en titane, à partir des données issues des essais cliniques.
Matériels et méthodes : Une recherche bibliographique systématique a été réalisée dans la base de données PubMed, conformément aux recommandations PRISMA, sans restriction quant à la date de publication. Seuls les essais cliniques prospectifs et randomisés menés chez l'être humain et permettant une comparaison entre les implants en titane et en zircone ont été retenus. Douze études répondaient aux critères d'inclusion. Les critères d'évaluation comprenaient le taux de survie implantaire, la perte osseuse marginale, la réponse des tissus péri-implantaires, les complications biologiques et mécaniques, ainsi que les résultats rapportés par les patients.
Résultats : Les taux de survie implantaire étaient élevés pour les deux matériaux, variant de 88,8 % à 100 %, sans différence notable rapportée au cours des périodes de suivi à court et à moyen terme. La perte osseuse marginale et la réponse des tissus mous étaient globalement comparables entre les deux groupes. Les complications biologiques étaient peu fréquentes et ne présentaient pas de différences clairement établies. En revanche, les implants en zircone semblaient présenter une tendance plus marquée aux complications mécaniques, notamment aux fractures dans les configurations monoblocs. Un léger avantage esthétique en faveur de la zircone était fréquemment rapporté.
Conclusion: Les implants en zircone semblent constituer une alternative fiable aux implants en titane dans certaines situations cliniques, avec des résultats comparables à court et à moyen terme. Néanmoins, leurs limites mécaniques et le manque de données à long terme demeurent des préoccupations importantes. Des essais cliniques randomisés supplémentaires, rigoureusement conçus et assortis d'un suivi prolongé, restent nécessaires.

MOTS-CLES : Implants dentaires ; titane ; zircone ; ostéointégration ; résultats cliniques.

* *Corresponding author.* Tel.: 00213699485030.
E-mail Address: hakimaouari@yahoo.fr

Received on: 28/04/2026
Revised on: 12/08/2026
Accepted on: 26/10/2026

1. Introduction

Tooth loss is a common clinical problem that can have significant consequences for masticatory function, aesthetics, and patients' quality of life. Oral implantology currently represents a reliable and frequently used method to restore function in partially or totally edentulous patients.

Since the pioneering contributions of Per-Ingvar Brånemark, titanium implants have been considered the gold standard in oral implantology. Their success is mainly based on their excellent biocompatibility and their ability to achieve stable and long-lasting osseointegration with bone [1-3].

Despite these highly satisfactory outcomes, certain limitations have been reported in the literature, particularly aesthetic concerns in the anterior region, especially when the gingival biotype is thin, as well as apprehension among some patients regarding the presence of metal in the body [4-6].

In this context, zirconia implants are considered a viable substitute [7]. Zirconia offers several advantages, including high biocompatibility, low affinity for bacterial plaque accumulation, and superior aesthetic properties due to its white color. Its use in implant dentistry is mainly aimed at improving aesthetics while providing a metal-free solution [8-11].

Over the past two decades, clinical studies, including randomized controlled trials, have evaluated the clinical performance of zirconia implants in comparison with titanium implants. This systematic review aimed to analyze data from clinical trials comparing titanium and zirconia implants with respect to implant survival, marginal bone loss, biological and technical complications, and aesthetic outcomes.

2. Materials and Methods

2.1. Article Selection (PRISMA)

A literature search was conducted in the PubMed database with no date restrictions, using MeSH terms and free-text keywords combined with Boolean operators:

("Dental Implants" [MeSH] OR "dental implant*" OR "oral implant*") AND ("Titanium" OR "titanium implant*") AND ("Zirconia" OR "zirconium dioxide" OR "ceramic implant*") AND ("osseointegration" OR "implant survival" OR "biocompatibility" OR "marginal bone loss" OR "peri-implantitis" OR "clinical outcome").

A supplementary search on Google Scholar was

conducted but not included due to a large number of irrelevant studies (reviews, in vitro studies, simulations). The analysis therefore focused on PubMed, which was deemed more appropriate for identifying structured clinical studies through the use of validated methodological filters.

Study selection followed an approach inspired by the PRISMA guidelines and took place in several stages: identification, screening (review of titles and abstracts), and eligibility assessment (review of full-text articles). Articles were included or excluded based on predefined criteria.

The inclusion criteria were prospective or randomized clinical trials, studies reporting relevant clinical data including implant survival, marginal bone loss, and complications, and studies conducted in humans. Literature reviews, systematic reviews, and meta-analyses were excluded, as were in vitro or animal studies, in silico studies, and studies lacking usable clinical data.

The search strategy initially identified 297 articles. After screening the titles and abstracts to assess their eligibility, the relevant articles were evaluated in full-text according to predefined inclusion and exclusion criteria. Thirty articles were selected for screening. Final inclusion: 12 articles. This stepwise selection process helped ensure the methodological quality of the included studies and allowed a consistent comparison of data between titanium and zirconia implants (Figure1).

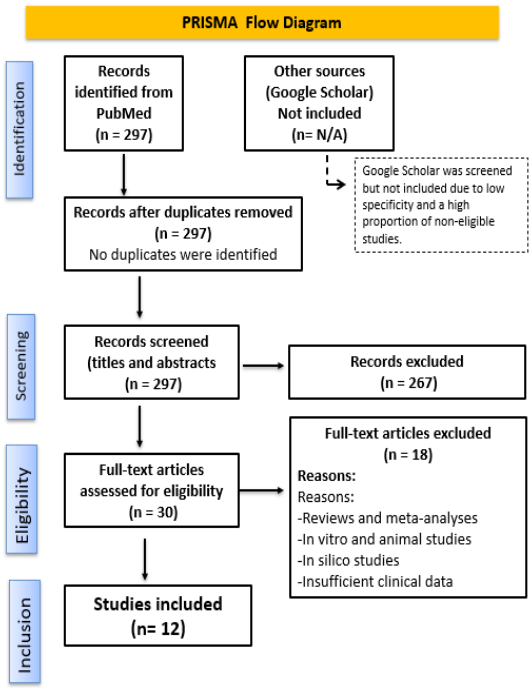


Figure 1: Selection procedure.

2.2. Analysis Criteria

The analysis of the selected studies focused on several key clinical and prosthetic criteria, including osseointegration, implant survival rate, marginal bone loss, soft tissue response, biological and mechanical complications, and patient satisfaction, comparing titanium and zirconia implants.

The studies included in this review are presented in tables and organized according to the following criteria: author/year and study type, population (patients/implants/ implant material evaluated), outcomes assessed, follow-up duration, implant survival rate, key findings, strengths, limitations, and conclusion (Table 1)

Table 1: Characteristics of included studies

Study	Study design	Population (patients / implants)	Outcomes assessed	Follow-up	Implant survival rate	Key findings	Strengths	Limitations	Conclusion
J H W de Beus, 2024	RCT prospective	49 patients (Zr :25 / Ti :24)	MBL, clinical parameters, aesthetics, PROMs	1 yr	Zr : 96% / Ti : 100%	No difference in MBL, high survival, comparable aesthetic results	RCT, standardized protocol	different implant designs	Zirconia = a viable short-term alternative

Michael Payer , 2015	RCT	22 patients, 31 implants (Zr :16 / Ti:15)	Survival, MBL, clinical indices, aesthetics	24 mo	Zr : 93.3% / Ti: 100%	Comparable survival and MBL	RCT, longitudinal	Small sample	Comparable results in the medium term
Guido Sterzenbach, 2025	RCT non-inferiority	60 patients (Zr :30 / Ti:30)	Survival, technical complications, aesthetics, PROMs	3 yrs	Zr: 89.3% / Ti: 100%	Non-inferiority not met	Robust design	Moderate sample	Zirconia is less reliable (osseointegration)
Yaniv Mayer, 2024	Prospective study (single-arm)	8 patients, 9 Zr implants	Survival, MBL, IL-1β, clinical	1 yr	Zr : 88.8%	Moderate MBL, low inflammation	Biological analysis	Very small sample	Limited evidence
Martin Koller 2020	RCT pilot	22 patients, 31 implants (Zr :16 / Ti :15)	Survival, IP, BOP, PES, MBL	80 mo	Zr : 87.5% / T i: 93.3%	No significant difference	Long-term FU	Low statistical power	Comparable outcomes
Ralf-Joachim Kohal, 2012	Prospective cohort	65 patients, 66 Zr implants	Survival, MBL, soft tissue	1 yr	Zr : 95.4%	High MBL (frequent >2 mm)	Larger sample	No control group	One-piece limitations
Andrea-Enrico Borgonovo, 2012	Prospective study	5 patients, 18 Zr implants	Survival, MBL, clinical	1–4 yrs	Zr : 100%	Good bone stability	Longitudinal	Very small sample	Favorable in selected cases
Reham B Osman, 2013	RCT overdenture	24 patients (Zr :12 / Ti :12)	Survival, MBL, complications	1 yr	Zr : 55–90% / Ti : 72–96%	More failures and fractures in Zr	RCT	Small sample	Zr Not recommended for overdentures
Kai-Hendrik Bormann , 2018	Prospective study	44 patients Zr	Survival, success, MBL, clinic	3 yrs	Zr : ~97.5%	Stable bone levels	Mid-term FU	No control group	Viable alternative in a simple case
Christian Blaschke, 2006	Clinical Study	34 patients, 66 Zr implants	Osseointegration, soft tissue, histology	2–5 yrs	Zr : ~98%	Excellent biocompatibility	Histological data	No control group	Strong biological response
Marc Balmer, 2026	Multicenter RCT	112 patients (Zr :61 / Ti :61)	MBL, survival, peri-implant health	1 yr	Zr : 100% / Ti : 96.5%	Equivalent outcomes	Multicentric , high power	Short FU	Short-term equivalence
Jantien H W de Beus,2024	Prospective study (single-arm)	30 patients, 30 Zr implants	Survival, MBL, complications, PROMs	5 yrs	Zr : 75.8%	Suboptimal survival outcome	Long-term FU	No control group	Less favorable results

The following abbreviations are used throughout this review: PROMs (Patient-Reported Outcome Measures), MBL (Marginal Bone Loss), PI (Plaque Index), PES (Pink Esthetic Score), BOP (Bleeding on Probing), RCT (Randomized Controlled Trial), FU (Follow-up), yrs (years), mo (months), vs (versus), Zr (zirconia), and Ti (titanium).

In addition, a comprehensive analysis of these studies was conducted to assess the clinical, radiographic and prosthetic outcomes of titanium and zirconia implants. The focus of the collected data was on implant survival rates, osseointegration quality, marginal bone loss, peri-implant soft tissue condition, and prosthetic complications.

3. Results

3.1. Study type

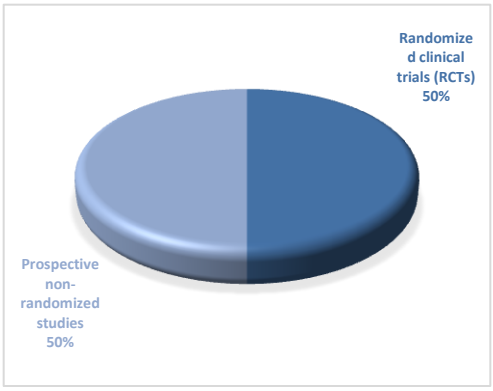


Figure 2: The distribution of studies according to methodological design.

The distribution of studies by methodological design is balanced between randomised controlled trials (RCTs) and uncontrolled prospective studies, with six studies in each category. While RCTs represent the highest level of evidence and allow for a direct comparison between zirconia and titanium implants, uncontrolled prospective studies provide complementary data from clinical conditions that more closely resemble everyday practice (Figure 2).

3.2. Follow-up period

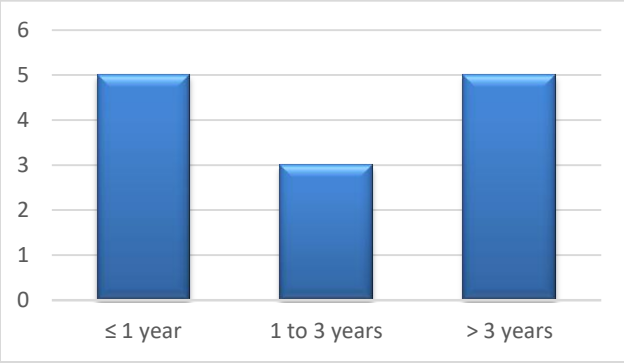


Figure 3: Distribution of studies according to the follow-up period.

The chart shows a relatively even distribution of studies across different follow-up durations. There are five studies with follow-up periods of ≤ 1 year, three with 1–3 years, and four with more than 3 years (Figure 3).

3.3. Implant Survival Rates

The included studies generally reported high implant survival, with rates ranging between 88.8% and 100% over follow-up periods ranging from six months to five years (Figure 3). Most controlled trials demonstrated survival rates exceeding 95%.

However, some long-term prospective studies report lower rates. Notably, one 5-year study showed survival rates dropping to approximately 75.8%, primarily due to early osseointegration failure (13.3%) and implant fracture (≈ 17%) [12]. Overall, zirconia implants perform similarly to titanium implants in the short to medium-term.

3.4. Osseointegration

Osseointegration of zirconia implants is generally satisfactory, with results comparable to those of titanium in several clinical studies. Histological and clinical evaluations demonstrate direct contact between bone and the implant, with no fibrous tissue layer observed in experimental models, as well as biological stability comparable to titanium [13-15]. However, some studies report cases of osseointegration failure associated with fibrous tissue interposition, particularly in two-piece implants, suggesting that this variability depends on implant design and mechanical conditions [12, 16-17].

3.5. Marginal bone loss (MBL)

Marginal bone loss generally ranges from 0.8 mm to 1.5 mm during the first three years, with stabilisation generally occurring within the first year. Randomised trials show no significant difference between zirconia and titanium [13, 15,18-20]. However, some studies indicate slightly higher bone loss for zirconia in specific contexts, such as overdentures or one-piece implants, though this does not exceed clinically acceptable thresholds [12,17].

3.6. Soft Tissue Integration

The peri-implant soft tissue evaluation was performed in several studies using plaque, bleeding, and calculus indices (Plaque Index, Bleeding Index, Calculus Index). The results demonstrate satisfactory tissue integration, with low plaque and bleeding indices, no suppuration, and limited inflammation. Zirconia implants demonstrated performance comparable to that of titanium implants, indicating favorable biocompatibility and adequate maintenance of peri-implant health [15,18-19, 21].

3.7. Biological and mechanical complications

The frequency of biological complications remains limited, similar to those observed with titanium, and consists primarily of isolated episodes of peri-implant mucositis [13,15,18,20]. Conversely, mechanical complications emerge as a substantial constraint for specific zirconia implants, manifesting as implant fractures and structural failures, particularly in long-

term studies or with one-piece implants [12,17]. Two-piece implants demonstrate superior mechanical performance; however, they are susceptible to intermittent technical complications [15, 16].

3.8. Patient Satisfaction

Patient satisfaction levels are typically high, with favorable ratings concerning aesthetics, masticatory function, and comfort [12, 16, 18]. This examination of the literature reveals an absence of statistically significant discrepancies between zirconia and titanium implants, as evidenced by comparative studies [16, 18]. In some cases, patients have reported a slightly better aesthetic perception with zirconia, due to the absence of metallic discoloration of the gums [15,19].

In summary, zirconia implants exhibit satisfactory clinical outcomes that are comparable to those of titanium for the majority of biological and functional parameters, particularly in the short and medium-term. However, variability is observed depending on the implant design and follow-up duration, particularly regarding mechanical complications and long-term survival.

4. Discussion

The distribution of literature demonstrates a balanced representation of controlled experimental evidence and observational clinical data. However, it is important to note that conclusions regarding zirconia implants are still based on a heterogeneous body of research, combining short- and medium-term randomized trials and prospective studies that are often limited in sample size and methodological controls. Among the 12 studies that were analyzed, this distribution translates into 6 randomized controlled trials that allow for a direct comparison of zirconia versus titanium, and 6 non-randomized prospective studies, mostly cohort or single-arm, providing complementary clinical data but with a lower level of evidence due to the absence of a control group.

With regard to implant survival, the majority of included studies revealed no clinically significant differences. The survival rate for zirconia implants is typically above 95%, which is comparable to the survival rate for titanium implants. This suggests that zirconia may be a viable alternative to titanium in certain cases where it is medically appropriate to use.

However, this apparent equivalence should be interpreted with caution due to the often-small sample sizes and sometimes insufficient statistical power to detect minute differences. Moreover, the majority of studies have been characterized by a limited follow-up period (ranging from one to five years) and have predominantly focused on a select array of clinical indications.

With regard to marginal bone loss, the results are heterogeneous. Some studies have been conducted that report comparable stability between the two materials. However, other studies have indicated a slight superiority of titanium. This phenomenon can be attributed to the material's well-established status and the extensive training clinicians have received in utilizing the established protocols. This variability can be attributed to significant methodological differences between studies, including design, type of implant connection, prosthetic protocol, lack of uniformity in bone loss measurement, and operator-dependent experience.

With respect to the soft tissue response and biocompatibility, a significant argument in favor of zirconia pertains to its interaction with soft tissues. The results of these studies generally indicate a reduction in peri-implant inflammation, with some studies reporting improved plaque control. Additionally, good epithelial attachment is observed in several studies. Zirconia appears to have a favorable affinity for gingival fibroblasts, which promotes their adhesion and proliferation, thus contributing to soft tissue stability [22-23]. In comparison with alternative materials, this material exhibits a reduced capacity for bacterial adhesion [24]. These properties may contribute to a reduction in the risk of peri-implant complications, although the data remain limited. However, the efficacy of these devices remains a subject of debate in the scientific community. Some studies have reported no significant differences in outcomes between these devices and titanium implants [25], with the results of the study seeming to be contingent upon the surface design and surgical protocol [26].

Technical complications are one of the main points of discussion regarding zirconia implants. One-piece implants present an increased risk of fracture and limited flexibility due to specific prosthetic constraints. Newer two-piece systems, such as those studied by Spies BC, appear to improve clinical flexibility while maintaining satisfactory performance [27].

However, zirconia exhibits a lower degree of durability than titanium. Its mechanical strength is susceptible to deterioration due to hydrothermal aging, and the implant-abutment connections are a critical point [28-30]. Consequently, while recent outcomes are encouraging, prudence is still advised, particularly in regions subject to elevated occlusal stress.

From an aesthetic perspective, zirconia implants offer a significant advantage due to their white color, which avoids the gray translucency sometimes observed with titanium implants, particularly in patients with a thin gingival biotype, especially in anterior areas.

As asserted by Aldhuwayhi, S. (2025), zirconia is particularly indicated in cases where aesthetic requirements are high [31-32]. However, it should be noted that the aesthetic outcome is contingent upon several factors, including implant position, gingival

thickness, and surgical and prosthetic techniques. Consequently, zirconia does not compensate for errors in planning or tissue management. In this particular context, the included studies have reported a general level of satisfaction, irrespective of the material used in the implant [33]. Nevertheless, a slightly superior aesthetic perception is sometimes observed with zirconia, which can positively influence patient satisfaction. This satisfaction is multifactorial in nature, encompassing functional comfort, aesthetic integration, the absence of complications, and the quality of the prosthetic fit.

Consequently, while zirconia implants are regarded as a credible substitute for titanium, exhibiting generally comparable clinical performance in the short and medium-term, they offer aesthetic advantages and a favorable biological response from soft tissues. Nevertheless, these devices continue to exhibit certain mechanical constraints and an absence of long-term data. The selection of implant material must, therefore, be tailored to the patient's specific clinical, aesthetic, and functional needs.

Moreover, the comprehensive interpretation of the results is constrained by considerable methodological heterogeneity. This heterogeneity is evident in the diversity of study designs, including randomized trials, prospective non-randomized studies, and single-arm studies. Additionally, it is observed in the heterogeneity of the study populations and the lack of uniformity in evaluation criteria. The existing body of literature also encompasses variations in surgical and prosthetic protocols, as well as in implant designs (one-piece versus two-piece). Additionally, there is a broad range of follow-up durations, generally ranging from the short to the medium term.

This methodological variability compromises direct comparability between studies and limits the generalizability of results. Additionally, the sample sizes are frequently limited, and the duration of the available data is often inadequate. Notably, none of the included studies report follow-up periods exceeding 10 years.

PubMed was selected as the primary database because of its relevance to biomedical and clinical research; however, searching additional databases could have improved the comprehensiveness of the review.

It is imperative to underscore that zirconia implants constitute a technology that is undergoing continuous refinement and development. The advent of novel generations of zirconia implants and treated surfaces has the potential to profoundly influence future outcomes and enhance their mechanical and biological performance.

5. Conclusion

Overall, zirconia implants show promising performance as an alternative to titanium implants during short- and medium-term follow-up. They present high survival rates, comparable marginal bone levels, and favorable peri-implant tissue integration. The primary benefit of these devices lies in their aesthetic potential, particularly in the anterior region and in patients with a thin gingival biotype. Nonetheless, certain limitations persist, particularly with regard to mechanical properties—particularly for one-piece systems—and the inadequate clinical evidence for two-piece zirconia implants.

Furthermore, the level of evidence remains limited due to methodological heterogeneity among the studies, small sample sizes, and the lack of long-term data. In this context, the selection of implant material must be customized to the specific needs of each patient, considering biomechanical constraints, aesthetic considerations, and the patient's profile. Conducting rigorous clinical studies with long-term follow-up is imperative to substantiate the durability of zirconia implants and elucidate their function in implantology.

6. Future perspectives

Research directions primarily concern confirming the long-term clinical performance of zirconia implants and strengthening the available evidence base. Randomized clinical trials with larger sample sizes and an extended observation period of 5 to 10 years are needed to assess their durability and biological and mechanical behavior. Particular attention should also be paid to two-piece zirconia implants, which could overcome the limitations of monobloc systems while maintaining the aesthetic appeal of the material, but for which clinical experience remains limited.

Finally, harmonizing clinical and radiographic evaluation protocols is essential to improve the comparability of studies and reduce current methodological heterogeneity.

Conflicts of interest

Authors do not declare any conflict of interest.

Acknowledgement

The author gratefully acknowledges Pr Mohamed Sid Ahmed for their valuable support in manuscript preparation and guidance on publication formatting requirements.

References.

1. Tafuri G, Santilli M, Manciocchi E, Rexhepi I,

D'Addazio G, Caputi S, et al. A systematic review on removal of osseointegrated implants: an update. *BMC Oral Health*. 2023;23(1):756. doi:10.1186/s12903-023-03456-5

2. Branemark PI. Osseointegrated implants in the treatment of the edentulous jaw. Experience from a 10-year period. *Scand J Plast Reconstr Surg Suppl*. 1977; 16:1-132.
3. Branemark PI. *Osseointegrated implants in the treatment of the edentulous jaw*. Stockholm : Almqvist & Wiksell; 1977.
4. Jung RE, Zembic A, Pjetursson BE, Zwahlen M, Thoma DS. Systematic review of the survival rate and the incidence of biological, technical, and aesthetic complications of single crowns on implants reported in longitudinal studies with a mean follow-up of 5 years. *Clin Oral Implants Res*. 2012;23 Suppl 6:2-21. doi:10.1111/j.1600-0501.2012. 02547.x
5. Schwarz F, Mihatovic I, Shirakata Y, Becker J, Bosshardt DD, Sculean A. Treatment of soft tissue recessions at titanium implants using a resorbable collagen matrix: a pilot study. *Clin Oral Implants Res*. 2014;25(1):110-5. doi:10.1111/clr.12083
6. Evrard L, Waroquier D, Parent D. Allergies to dental metals. Titanium: a new allergen. *Rev Med Brux*. 2010;31(1):44-9.
7. Özkurt Z, Kazazoğlu E. Zirconia dental implants: a literature review. *J Oral Implantol*. 2011;37(3):367-76. doi:10.1563/AAID-JOI-D-10-00014
8. De Wijs FL, Van Dongen RC, De Lange GL, De Putter C. Front tooth replacement with Tubingen (Frialit) implants. *J Oral Rehabil*. 1994; 21:11-26.
9. Schulte W, d'Hoedt B. 13 Jahre Tubinger Implantat aus Frialit – Weitere Ergebnisse. *Z Zahnärztl Implantol*. 1988; 3:167-72.
10. Hisbergues M, Vendeville S, Vendeville P. Zirconia: established facts and perspectives for a biomaterial in dental implantology. *J Biomed Mater Res B Appl Biomater*. 2009;88(2):519-29. doi:10.1002/jbm.b.31147
11. Gahlert M, Gudehus T, Eichhorn S, Steinhauser E, Kniha H, Erhardt W. Biomechanical and histomorphometric comparison between zirconia implants with varying surface textures and a titanium implant in the maxilla of miniature pigs. *Clin Oral Implants Res*. 2007;18(5):662-8. doi:10.1111/j.1600-0501.2007. 01389.x
12. Beus JHW, Cune MS, Meijer HJA, Raghoebar GM, Schepke U. Metal-free custom-made zirconia implants: a prospective 5-year follow-up single-arm clinical trial. *Clin Implant Dent Relat Res*. 2025;27(1): e13404. doi:10.1111/cid.13404
13. Bormann KH, Gellrich NC, Kniha H, Schild S, Weingart D, Gahlert M. A prospective clinical study to evaluate the performance of zirconium dioxide dental implants in single-tooth edentulous area: 3-year follow-up. *BMC Oral Health*. 2018;18(1):181. doi:10.1186/s12903-018-0636-x
14. Blaschke C, Volz U. Soft and hard tissue response to zirconium dioxide dental implants: a clinical study in man. *Neuro Endocrinol Lett*. 2006;27 Suppl 1:69-72.
15. Balmer M, Payer M, Steinwender A, Herber V, Jung RE, Kühl S. One-year analysis of clinical and radiological outcomes of two-piece zirconia compared to titanium implants: a multicenter prospective randomized clinical trial. *Clin Oral Implants Res*. 2026;37(4):496-508. doi:10.1111/clr.70094
16. Sterzenbach G, Richter K, Alpen K, Khoshreza H, Beuer F, Thiele T. A randomized controlled trial evaluating 3-year survival rates and technical complications of screw-retained hybrid abutment crowns on two-piece zirconia and titanium implants. *Clin Oral Implants Res*. 2025;36(8):965-77. doi:10.1111/clr.14443
17. Osman RB, Swain MV, Atieh M, Ma S, Duncan W. Ceramic implants (Y-TZP): are they a viable alternative to titanium implants for the support of overdentures? A randomized clinical trial. *Clin Oral Implants Res*. 2014;25(12):1366-77. doi:10.1111/clr.12272
18. De Beus JHW, Cune MS, Slot JWA, Jensen-Louwerse C, La Bastide-Van Gemert S, Meijer HJA, et al. A randomized clinical trial on zirconia versus titanium implants in maxillary single tooth replacement. *Clin Oral Implants Res*. 2024;35(6):630-40. doi:10.1111/clr.14258
19. Payer M, Heschl A, Koller M, Arnetzl G, Lorenzoni M, Jakse N. All-ceramic restoration of zirconia two-piece implants: a randomized controlled clinical trial. *Clin Oral Implants Res*. 2015;26(4):371-6. doi:10.1111/clr.12342
20. Koller M, Steyer E, Theisen K, Stagnell S, Jakse N, Payer M. Two-piece zirconia versus titanium implants after 80 months: clinical outcomes from a prospective randomized pilot trial. *Clin Oral Implants Res*. 2020;31(4):388-96. doi:10.1111/clr.13576
21. Mayer Y, Ginesin O, Rotenberg D, Kabakov L, Gabay E, Horwitz J, et al. Survival rate and esthetic outcomes of 2-piece zirconia dental implants: a 1-year clinical trial. *J Oral Implantol*. 2024;50(6):563-8. doi:10.1563/aaid-joi-D-24-00027
22. Tetè S, Zizzari VL, Borelli B, De Colli M, Zara S, Sorrentino R, et al. Proliferation and adhesion capability of human gingival fibroblasts onto zirconia, lithium disilicate and feldspathic veneering ceramic in vitro. *Dent Mater J*. 2014;33(1):7-15. doi:10.4012/dmj.2013-185
23. Hu J, Qie Y, Luo Y, Jiang Q. Effect of porous zirconia coating on human gingival fibroblasts and its mechanism. *J Biomed Nanotechnol*. 2022;18(4):1164-71. doi:10.1166/jbn.2022.3317
24. Rimondini L, Cerroni L, Carrassi A, Torricelli P. Bacterial colonization of zirconia ceramic surfaces: an in vitro and in vivo study. *Int J Oral Maxillofac Implants*. 2002;17(6):793-8.

25. Van Brakel R, Meijer GJ, Verhoeven JW, Jansen J, De Putter C, Cune MS. Soft tissue response to zirconia and titanium implant abutments: an in vivo within-subject comparison. *J Clin Periodontol*. 2012;39(10):995-1001. doi:10.1111/j.1600-051X.2012. 01931.x
26. Jin HW, Noumbissi S, Wiedemann TG. Comparison of zirconia implant surface modifications for optimal osseointegration. *J Funct Biomater*. 2024;15(4):91. doi:10.3390/jfb15040091
27. Spies BC, Nold J, Vach K, Kohal RJ. Two-piece zirconia oral implants withstand masticatory loads: an investigation in the artificial mouth. *J Mech Behav Biomed Mater*. 2016; 53:1-10. doi: 10.1016/j.jmbbm.2015.07.005
28. Denry I, Kelly JR. State of the art of zirconia for dental applications. *Dent Mater*. 2008;24(3):299-307. doi: 10.1016/j.dental.2007.05.007
29. Chevalier J. What future for zirconia as a biomaterial? *Biomaterials*. 2006;27(4):535-43. doi: 10.1016/j.biomaterials.2005.07.034
30. Bergamo ETP, Campos TMB, Lopes ACO, Cardoso KB, Gouvea MVR, de Araújo-Júnior ENS, et al. Hydrothermal aging affects the three-dimensional fit and fatigue lifetime of zirconia abutments. *J Mech Behav Biomed Mater*. 2021; 124:104832. doi: 10.1016/j.jmbbm.2021.104832
31. Gul A, Bureau E, Becktor JP, Vult von Steyern P, Papia E. Stress evaluation in one-piece and bone- or tissue-level two-piece zirconia dental implants with ceramic or titanium abutment screws: a finite element analysis. *BMC Oral Health*. 2026. doi:10.1186/s12903-026-08192-y
32. Aldhuwayhi S. Zirconia in dental implantology: a review of the literature with recent updates. *Bioengineering (Basel)*. 2025;12(5):543. doi:10.3390/bioengineering12050543
33. Khzam N, Arora H, Kim P, Fisher A, Mattheos N, Ivanovski S. Systematic review of soft tissue alterations and esthetic outcomes following immediate implant placement and restoration of single implants in the anterior maxilla. *J Periodontol*. 2015;86(12):1321-30. doi:10.1902/jop.2015.150287