

Review Article

Clinical Guideline for Zirconia Dental Implants: A Comprehensive and Critical Review and Update

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Abstract

Zirconia implants have become a very promising alternative to conventional titanium implants for oral rehabilitation with superior biological and esthetical properties. An electronic search through PubMed about zirconia dental implants has been performed in the English language. Zirconium dioxide implants demonstrate excellent biocompatibility, gingival adhesiveness and esthetic benefits. The evidence for one-piece ceramic implants has become strong enough that these implants have a similar range of indications as titanium implants and can be used in the same situations. However, lack of evidence for long-term success of two piece zirconia Implants above 5 years are considered to be a drawback.

Keywords: Zirconia Implant; Zirconia Oral Implant, Ceramic Implant; Dental Implant; Osseointegration; Titanium Intolerance

Introduction

Dental implants refer to osseointegrated pillars that include single-tooth crowns, bridge restorations and implants as pillars for removable prosthodontic restorations being used as a therapeutic option in the rehabilitation of partial edentulous or fully edentulous jaws. The inclusion of dental implants in the treatment of missing teeth is part of the differential therapeutic planning and is balanced against tooth-borne fixed and removable dental prostheses in the specific patient situation as part of the treatment decision. While surface-modified titanium implants have established themselves as the gold standard in clinical practice over the past 45 years based on numerous prospective long-term studies and experiences, corresponding long-term experience and data for modern ceramic implant systems are still pending despite

promising 3- and 5-year data.

The development of ceramic implants and their clinical use has been documented since the 1960s, but ongoing material innovations and the use of non-commercially available implant types have led to an inconsistent and therefore less comparable study situation. Formerly, the starting material for dental ceramic implants was Aluminum Oxide (Al_2O_3). Although rarely declared as a cause of failure in the records of clinical studies, it was associated with higher implant fracture rates and failures in the healing phase. Consequently, aluminum oxide implants were withdrawn from the market in the early 1990s. Introduced in 2001, zirconium dioxide (ZrO_2) is now the standard material for ceramic implants and exhibits significantly more advantageous material properties compared to its predecessor, aluminum oxide, which are similar and comparable to those of titanium implants in many aspects (high flexural strength (900-1200 MPa), fracture toughness (6-9 MPa), bone-implant contact and influence on surrounding soft tissue). Yttria-stabilized tetragonal polycrystalline zirconia (Y-TZP) is the most commonly used variant due to its special mechanical properties [1-3]. Due to these superior biomechanical properties compared to Al_2O_3 , zirconia dental implants meet the material-specific requirements to withstand the masticatory forces in the oral cavity. However, unlike titanium, the essential properties depend significantly on the type and quantity of dopants and additives, as well as the manufacturing process, i.e., on the respective expertise of the manufacturer [4,5]. The aim of this article is to address all implant provider specialists with a scientifically systematic explanation of treatment with dental ceramic implants and to provide decision-making support for indications in everyday care.

Material and Methods

An electronic search through PubMed to retrieve information about advantages and disadvantages of zirconia dental implant regarding chemical, physical and mechanical properties, osseointegration, surface modification, biocompatibility, soft tissue response and success rates has been performed. The search was limited to articles in the English language, published until February 2024.

Ethical Statement

The project did not meet the definition of human subject research under the purview of the IRB according to federal regulations and therefore, was exempt.

Review

General Aspects of Dental Ceramic Implants

Commercially available ceramic implants consist almost exclusively of zirconium dioxide (zirconia, ZrO_2), whereby the terms zirconium or zircon are often colloquially but incorrectly used. Zirconium is the pure metal, whose element can be found in the 4th group of the periodic table, identical to titanium. Conversely, Zircon is the silicate sand zirconium silicate (ZrSiO_4), which can be converted into zirconium dioxide in various other technical processes. The alienation of elemental affiliation occurs during the processing of zircon. While very thin but stable passivation layers of titanium dioxide are formed in contact with oxygen with commercially available pure titanium-based implants, zircon is fully oxidized with a microcrystalline structure during its processing into a complete ceramic: this means that the oxygen or the oxide has become an integral part of the solid material and physiologically speaking, is a completely different material than the metal zirconium. Zirconia consists of ionic (approx. 70%) and covalent (approx 30%) bonds (no metallic bonds). For this reason, ceramics belong to the group of non-metallic materials, although the term "zirconium" is found in the term "zirconium dioxide" [1-5].

These facts must also be considered when interpreting studies that have demonstrated the elements "zirconium" and "titanium" on the surface and in the vicinity of zirconia implants through different analysis methods [5-8]. However, the described analytical techniques can only detect individual elements, i.e., they cannot differentiate whether the element zirconium is present individually or as a compound in the zirconium dioxide ceramic. Furthermore, these studies did not demonstrate systemic release and the biological effect of the mentioned elements or contaminations was doubted due to extremely low concentrations [8,9]. The zirconia dioxide structures are characterized by three crystal forms: monoclinic, cubic and tetragonal. Of importance in this context is the so-called phase transformation of zirconia. This refers to the transition from a fracture-resistant phase (tetragonal phase) to a more fracture-prone phase (monoclinic phase). This transformation is associated with a volume expansion and can stop the propagation of mechanically induced microcracks in the material structure (so-called "fracture toughening" mechanism) [6,10-13,15]. However, to counteract an unfavorable unwanted phase transformation from the tetragonal to the monoclinic state from a biomechanical perspective, a grain size reduction to 400 nm and 2-3 vol.-% of stabilizing yttrium oxide was doped [10]. As a result, in yttrium-oxide-stabilized tetragonal zirconia polycrystals (Y-TZP), the required amount of energy that leads to the undesired phase transformation from tetragonal to monoclinic at room temperature increases [11]. By additionally doping with alumina (volume fraction of 20%), the material properties of TZP are further enhanced towards an increase in flexural strength to 2000 MPa (titanium: 400 MPa) and give the latest generation of zirconia the appended name "alumina-toughened zirconia (ATZ)". Both in Y-TZP and ATZ, a slow progression of phase transformation from tetragonal to monoclinic, also known as aging, in a moist environment is very unlikely and therefore, aging processes of ceramic dental implants play a rather subordinate clinical role [12,13]. Previous *in-vitro* studies have shown that in zirconia dental implants, the degree of phase transformation from tetragonal to monoclinic increases with increasing aging time, but this does not negatively affect the biomechanical fatigue strength of ZrO_2 dental implants [13-15]. However, since long-term follow-up data of more than 5 years are scarce, a clinical assessment of the mechanical long-term stability can only be made to a limited extent. Despite the promising material properties, the development of even more powerful ceramics seems not to be completed. This fact is all the more important since in zirconia dental implants, the manufacturing processes of the implants and in particular the methods for creating micro-rough surfaces have a decisive influence on the biomechanical long-term stability. In this context, it has been shown that by optimizing manufacturing processes, the fracture susceptibility of zirconia implants could be reduced from 3.4% to 0.2% between 2004 and 2020 [16,17]. The continuous further development of production processes and the associated product changes, however, lead to regular "de-actualization" of existing study data and delay the gain of knowledge from long-term studies. For example, this can be demonstrated by an ongoing long-term study with seven-year data on a two-part ceramic

implant by the authors Cionca, et al. Due to the discontinuation of the implant type used in the study in favor of the follow-up product with a different material composition, the study contents are not reproducible and thus reduced in meaningfulness [18]. Moreover, a meta-analysis reported that the different physical properties of implant systems from different manufacturers have a significant influence on the survival rates of zirconia implants [16].

Test for Material Incompatibility / Allergy

Material incompatibilities and intolerance reactions to metallic components (especially titanium) of dental implants have been discussed for some time [22,23-54]. Due to the heterogeneous state of studies, the value of a basic "prophylactic" allergy/incompatibility test (screening) without anamnestic allergic symptoms to predict the development of sensitization cannot be scientifically proven. Diagnostic testing for titanium intolerance has a longstanding, unreliable and frustrating history. Currently, there is no gold standard diagnostic tool in place to assess titanium intolerance or hypersensitivity. Nevertheless, literature has identified different techniques such as the Epicutaneous Patch Test, Lymphocyte Transformation Test (LTT) and Memory Lymphocyte Immunostimulation Assay (MELISA) [52,54]. In summary, generalized preoperative screening as a clinical standard protocol cannot be recommended at this time since MELISA and LTT require a prior sensitization to indicate Titanium intolerance and should only be applied when a patient is suspected of having a Titanium intolerance condition [52,54].

Osseointegration of Ceramic Implants

Osseointegration, defined as functional ankylosis, is a dynamic process consisting of primary and secondary stability [24]. In contrast to mechanically induced primary stability, secondary stability arises as a result of cellular activity with new bone attachment to the implant surface, akin to functional ankylosis [25]. The biological cascades involved in this process can be modified through implant surface modifications to accelerate and intensify osseointegration. The time period until stable bone formation is estimated to be eight to twelve weeks in general [26,27]. Similar to titanium implants, surface modification of zirconia dioxide implants can lead to differences in osseointegration. Preclinical animal studies have examined bone attachment to zirconia dioxide implants with various surface modifications such as sandblasting, etching sandblasting and acid etching sintering and coating showing that even subtle changes to the surface can have a significant impact on osseointegration [28-30,31,55]. In this context, a systematic review has demonstrated that increased surface microroughness is associated with faster and more stable osseointegration and that micro-rough zirconia oxide implants exhibit equivalent hard and soft tissue integration to titanium implants [32]. Furthermore, a study on human biopsies from 22 failed zirconia dioxide implants (failure due to trauma or peri-implantitis-related bone loss) revealed dense, uninterrupted bone with stable lamellar structure in close contact with the implant surface. The Bone-Implant Contact (BIC) ranged from 58.1 to 93.7% (mean: 76.5%) [33]. Since clinical success in the absence of clinical and radiological signs of inflammation can be considered indicative of successful osseointegration, clinically uneventful observation periods serve as a surrogate parameter. In this context, clinical studies on modern ceramic implants have shown similar success rates to titanium implants over follow-up periods of up to 7 years [16,18,19,34,35,53].

Plaque Accumulation/Peri-implant Infection Risk

Peri-implantitis is an inflammatory process around an osseointegrated implant, involving inflammation of the soft tissue and progressive loss of supporting bone beyond biological bone remodeling [36]. This inflammatory process is the main cause of long-term implant loss. Peri-implantitis results, among other factors, from biofilm dysbiosis surrounding the peri-implant mucosa, meaning that the colonization of specific bacteria is relevant to the development of the inflammatory reaction. Moreover, it is assumed that plaque accumulation and thus the risk of peri-implantitis is lower with ceramic implants compared to titanium implants [37]. Evidence for this has so far only emerged from *in-vitro* and animal studies [38-40]. Initial stable clinical indications of a lower risk of peri-implantitis with ceramic implants were found in a clinically prospective study involving a patient cohort with one ceramic and one titanium implant each. The highest bacterial load was observed on titanium implants, followed by zirconia oxide implants and natural teeth. At the same time, the peri-implant soft tissue inflammatory reaction around the examined titanium implants was the most pronounced [41]. These results were confirmed in a recent Randomized Clinical comparative study (RCT) involving 42 patients, each with one ceramic and one titanium implant [42].

Implant Survival and Implant Success with Ceramic Implants

The use of ceramic implants for replacing missing teeth can be evaluated in terms of implant survival and success at the time of this literature review for this article, only based on 8 clinically prospective studies and 3 reviews. The clinical studies consist of 2 Randomized Controlled Trials (RCT) and 6 cohort studies (non-RCT). The reviews consist of 1 meta-review and 2 systematic

reviews [46-48].

Implant survival is a clearly defined endpoint in the therapy with dental implants, which is reported in most clinical studies. In contrast to implant survival, implant success is inconsistently defined. Frequently applied principles in the literature refer to the concepts of implant success- defining criteria according to Albrektsson, et al., Smith, et al. or Buser, et al. For evaluation, the included studies were divided according to the implant design used (one- or two-piece) [43-45].

1. One-Piece Ceramic Implants

One-piece systems consist of an inseparably connected implant body with the abutment. In addition to the advantage of the absence of the implant-abutment interface, this in turn does not allow for a completely soft tissue closure (transgingival healing), limits the options for simultaneous augmentation measures and stress-free healing. Considering the results of previous and clinical prospective 3-year studies included in this guideline with observation periods of up to 7 years, as well as implant survival rates >97%, the use of one-piece ceramic implants based on zirconia can be classified as a valid treatment option [46,48]. Individual surgical and prosthetic protocols should be followed. In this context, Balmer, et al., 2018 were able to show an implant survival of 98.5% for one-piece ceramic implants based on zirconia in a clinical prospective 3-year study with single crowns and implant-supported bridge restorations [46]. Similarly high survival rates of one-piece ceramic implants with single tooth crowns were demonstrated by Bormann, et al., 2018 with 97.5% in a clinical prospective 3-year study [20]. In follow-up studies by the author groups led by Balmer, et al., and Kohal, et al., the 5-year data showed an almost unchanged survival rate of one-piece ceramic implants with single tooth crowns and bridge restorations as superstructures [19,47]. With a 7.8-year observation period, Lorenz et al. 2019 published the highest long-term data on one-piece dental ceramic implants with single crown restorations. The survival rate was 100% with 83/83 implants [35].

2. Two-Piece Ceramic Implants

While titanium implants have been available for a long time, the predominantly used two-piece implants today, on the other hand, ensure stress-free subgingival healing, thereby allowing for simultaneous peri-implant augmentation measures and at the same time offering more flexibility in the prosthetically axially oriented surgical implant insertion. In this context, it could be demonstrated in a systematic review that the implant design one-piece versus two-piece had no significant influence on survival rates [16].

While initial clinical retrospective data on two-piece non-commercially available ceramic implant systems were already published in 2014, the level of evidence for commercial products remains low and a conclusive evaluation for long-term clinical benefit (2 clinical studies; 1x RCT and 1x non-RCT) with an observation period of >6 years) compared to titanium implants as the gold standard is not possible. This creates a special need for patient education regarding the therapy with two-piece ceramic implants while considering the lack of long-term data compared to titanium implants as the current gold standard [16-20].

Conclusion

This critical literature review confirms that one-piece ceramic implants based on zirconia dioxide represent a valid and viable alternative to titanium implants, although they have not yet reached the long-term data that titanium implants have. The quality and stability of ceramic implants depend heavily on the manufacturers' production processes. While preclinical and clinical studies show positive results for osseointegration, there are no evidence-based statements regarding plaque accumulation and peri-implantitis risk, making it necessary to provide special information to patients. However, the evidence for one-piece ceramic implants has become strong enough to make a recommendation. These implants have a similar range of indications as titanium implants and can be used in the same situations. In contrast, the evidence for two-piece ceramic implants is still much thinner. There are still no long-term data for these implants, with a minimum period of five years. They should only be used after thorough information of the patient. It is also important to explain that theoretically, a material intolerance to titanium cannot be excluded. When informing patients about ceramic implants, we must point out that they may not cause intolerances and therefore may be an alternative for patients who have an intolerance to titanium. In the author's opinion, ceramic implants will take a firm place in the implant market over the next five to ten years, much like titanium implants. Currently, ceramic implants account for about 3 to 5 percent of the overall market. However, it is expected that their share will increase to up to 30 percent. The establishment of ceramic implants will continue and they will prevail in the market in the long term. Patients are aware of the availability of zirconia implants on the market and we need to be ready to respond to their demands.

Conflict of Interests

The authors declare no conflict of interest regarding authorship roles or publication of article.

Consent

Not applicable because this study is based exclusively on published literature.

Disclosure

The authors report no conflicts of interest.

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Authors Contribution

All the authors have equal contribution and all the authors have read and agreed to the published version of the manuscript.

Data Availability

Not applicable

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