

An Overview of Zirconia Dental Implants: Basic Properties and Clinical Application of Three Cases

Merve Bankoğlu Güngör, DDS, PhD^{1*}
 Cemal Aydın, DDS, PhD¹
 Handan Yılmaz, DDS, PhD¹
 Esma Başak Gül, DDS, PhD²

Due to the possible aesthetic problems of titanium implants, the developments in ceramic implant materials are increasing. Natural tooth colored ceramic implants may be an alternative to overcome aesthetic problems. The purpose of this article is to give information about the basic properties of dental zirconia implants and present 3 cases treated with two-piece zirconia implants. Two-piece zirconia dental implants, 4.0 mm diameter and 11.5 mm in length, were inserted into maxillary incisor region. They were left for 6 months to osseointegrate. Panoramic and periapical radiographs were obtained and examined for bone-implant osseointegration. During the follow-up period the patients were satisfied with their prosthesis and no complication was observed.

Key Words: dental implants, zirconia, zirconium oxide

INTRODUCTION

Since their introduction over 40 years ago, dental implants have been used to support fixed or removable dentures and have become an established treatment modality.^{1,2} Pure titanium is generally used for dental implants because of its biocompatibility and suitability for tooling.^{3,4}

Using conventional titanium implants to replace missing teeth may often be perceived through the peri-implant mucosa impairing aesthetic outcomes and can cause an unaesthetic appearance because of the dark colour of titanium.⁵⁻⁷ Also, the implant head may be visible because of soft tissue shrinkage, recessions, and peri-implant lesions.^{5,8} Further, although titanium has resistance to corrosion, investigations have shown increased titanium concentration in bone near titanium implants⁹ and in regional lymph nodes—but clinical findings are

not yet clear¹⁰—and after contact with saliva, galvanic side effect of titanium is also described.¹¹

In the late 1960s, ceramic implants made of Al₂O₃ (polycrystals or single crystal) have been considered as an alternative treatment for improved aesthetics.¹²⁻¹⁴ The first ceramic oral implant was crystalline bone screw implants produced by Sandhaus, who later introduced the Cerasand oral implant.¹³⁻¹⁵ In the middle of the 1970s, the implant known as the “Tübingen Implant (Frialit 1)” was introduced.^{13,16-20} A decade after the Tübingen Implant, the Bionit implant system and, in the early-to mid-1980s, ceramic anchor implants were produced. Aside from polycrystalline aluminium oxide, single crystal alumina (sapphire)—known as the “Bioceram implant”—has also been used as an implant material.^{13,21-26} These implants needed large geometric dimensions, so the indication of these implants was limited. However, their surface qualities achieved predictable bone and soft tissue healing.²⁶ Aluminium oxide- or alumina-based implants are osseointegrated well, but they are not available in the market because of their insufficient physical properties during long-term load.^{12,13}

In recent years, zirconia (Y-TZP; yttria tetragonal

¹ Department of Prosthodontics, Faculty of Dentistry, Gazi University, Ankara, Turkey.

² Department of Prosthodontics, Faculty of Dentistry, Inonu University, Malatya, Turkey.

* Corresponding author, e-mail: mervebankoglu@yahoo.com

DOI: 10.1563/AAID-JOI-D-12-00109

zirconia polycrystals), a high strength ceramic material with good long-term results in the field of medical implants, has been suggested as an alternative for dental implants. Y-TZP has higher resilience and flexural strength than aluminium oxide and offers advantages over aluminium oxide for dental implants.²⁷⁻³³ Will zirconia implants become an alternative to titanium implants?

PROPERTIES OF ZIRCONIA IMPLANTS

Y-TZP is a high strength ceramic material comprised of ZrO_2 and Y_2O_3 particles. It forms a stable tetragonal structure at room temperature after sintering. The transformation toughening mechanism is one of the main reasons for the high strength and toughness of Y-TZP.^{28,31,34}

Y-TZP is a bioinert and nonresorbable metal oxide that has excellent resistance to corrosion and wear, Young modulus similar to stainless steel alloy, high flexural strength (900–1.200 MPa), Vickers hardness (1.200) and Weibull modulus (10–12), high fracture resistance, high radiopacity, low thermal conductivity, an ivory color similar to the color of the natural tooth, ability to be machined, light transmitting, and good biocompatibility.^{1,2,7,12,27,28,35-41} Despite these advantages, zirconia can undergo low-temperature degradation that is identified as a surface transformation from tetragonal phase to monoclinic phase in water, water vapor, or aqueous solutions; this process may affect the microstructure and physical properties of zirconia.⁴² However, preparation and cyclic loading can decrease the fracture strength resistance of the zirconia implants³⁴ and fractures can occur in smaller diameters (3.25 mm).³⁵ Exploiting advances in nanotechnology, Ce-TZP/ Al_2O_3 nanocomposite has been introduced, offering superior mechanical properties compared to conventional Y-TZP,⁴³⁻⁴⁵ but there are not any published data on using Ce-TZP/ Al_2O_3 nanocomposite as a dental implant base material.

Zirconia has been shown to be as biocompatible as titanium.^{46,47} *Biocompatibility* is defined as the biomaterial or its degradation products that are not responsible for inflammatory reactions.²⁸ Zirconium oxide provokes less reaction in tissues than do other restorative materials, such as titanium.⁴⁶ Degidi et al⁴⁷ confirmed this result and reported that the level of the bacterial products measured with nitric oxide

synthase, inflammatory infiltrate, microvessel density, and vascular endothelial growth factor expression were found higher around the titanium caps than around the ZrO_2 ones. Zirconia can up- or down-regulate gene expressions, so zirconia can be a self-regulatory material that can modify turnover of the extracellular matrix.⁴⁸

Direct contact between the implant and surrounding bone is a parameter of clinical success.²⁸ Animal studies have demonstrated that zirconia implants showed direct bone apposition, and it has been concluded that osteoblastic cells have good proliferation and surface attachment to zirconia.^{1,2,12,26,29,49}

Hoffmann et al² evaluated the zirconia implant bone interface histologically in rabbits. Four zirconia and 4 titanium implants were placed. The area of bone-implant contact was evaluated, and the results demonstrated a similar rate of bone apposition on zirconia and surface-modified titanium implant surfaces during early healing.²

In 2 animal studies, Depprich et al^{1,29} investigated the osseointegration of zirconia implants. The results showed that there was no osseointegration difference on zirconia implants with modified surfaces and titanium implants with a similar surface topography.^{1,29} Histological results showed direct bone contact on the zirconia and titanium surfaces. It was demonstrated that zirconia implants with modified surfaces resulted comparable osseointegration with titanium implants.¹ Gahlert et al⁴⁹ confirmed these results in an histomorphometrical study. In another study, Gahlert et al²⁶ investigated 2 different zirconia surfaces (machined and sandblasted) topographies biomechanically and histologically with titanium sandblasted and acid-etched surfaces. Thirteen adult miniature pigs received 78 implants. After a healing period of 4, 8, and 12 weeks, implants were subjected to removal torque tests and then analyzed for direct bone apposition under a light microscope. The results showed that surface topography affected the osseointegration period. The acid-etched and sandblasted titanium surfaces had the highest removal torque values, and the machined zirconia surfaces had the lowest values.

Kohal et al¹² investigated the biomechanical and histological behavior of zirconia implants in rats. Four groups of implants were evaluated: machined zirconia implants, zirconia implants with a roughed

surface, machined titanium implants, and titanium implants with an electrochemically roughened surface. The results showed that all tested zirconia and titanium implant surfaces were biocompatible and osseointegrative. Surface modification of zirconia implants showed no difference with the electrochemically modified titanium implant surface when the histological and biomechanical results were compared.¹²

Kohal et al⁵⁰ evaluated the osseointegration of custom-made zirconia and titanium implants. Twelve custom-made zirconia and 12 custom-made titanium implants were inserted in extraction sites in 6 monkeys. The titanium implants were sandblasted and acid etched; the zirconia implants were only sandblasted. Six months after the implant insertion, single crowns were made and, after 5 months delivery of the crowns, the implants with the surrounding hard and soft tissue were harvested. No statistically significant differences were found in soft tissue when the results evaluated under the light microscope. The connective tissue attachment (distance between the apical end of the junctional epithelium and first bone-to-implant contact) were similar; however, titanium implants showed a greater extension. The mean mineralized bone-to-implant contacts after a 9-month healing period were 72.9% for titanium implants and 67.4% for zirconia implants.

Animal studies showed similar osseointegration values for zirconia implants in comparison with titanium implants, but these studies have limited numbers of samples and include only the short-term histological results.^{12,26,29,49} Long-term examinations of zirconia implants are limited to establish their clinical performance and success.

Payer et al⁵¹ evaluated clinical and radiographic outcomes of immediately provisionalized one-piece zirconia implants (WhiteSKY). A total of 20 implants were inserted in 20 patients. Observed bone loss was 1.29 mm after the 24-month follow-up period. In another study, Kohal et al⁵² investigated the clinical and radiographic outcomes of Zi Unite (Nobel Biocare, Gothenburg, Sweden) one-piece zirconia implants after a 1-year follow-up. The marginal bone loss was 1.31 mm, and the survival rate was 95.4%.

Only the immediate loaded one-piece implants were investigated in these studies,^{51,52} and it was concluded that there was not any problem on the

osseointegration of zirconia implants but the observed bone loss was higher than 0.2 mm, which was reported as an implant success criteria for titanium implants after 1 year by Smith and Zarb.⁵³ Long-term clinical study results with two-piece titanium implants showed higher success rate and lower bone resorption when compared with one-piece zirconia implants.^{54–56}

Biocompatibility of the zirconia has been proven in several animal investigations, but there are insufficient studies focusing on the physical properties of zirconia implants.^{12,34}

Çağlar et al^{57,58} investigated the one-piece zirconia implants in 2 biomechanical studies: In the first, the titanium and yttrium-stabilized zirconium implants were compared in three-dimensional finite element analysis. The zirconia implant generated the lowest stresses in cortical bone, and the zirconia abutment resulted in lower vonMises and compressive stresses than did the titanium abutment in implant and cortical bone.⁵⁷ In the second study, 3 different zirconia dental implants were compared, and the higher stresses were evaluated.⁵⁸

Silva et al⁶ tested influence on fatigue reliability and failure modes between as-received and after crown preparation on one-piece ceramic implants. Forty-eight one-piece Y-TZP ceramic implants were evaluated. Results showed that crown preparation did not influence the reliability of the one-piece ceramic implant, and fatigue did not influence the lifetime of ceramic implants at loads under 600 N.⁶

In another study, Gahlert et al³⁵ investigated the failure of fractured zirconia dental implants. In this study, 170 implants were inserted in 79 patients, and the results showed that fracture rate of nearly 10% within a follow-up period of 38 months after prosthetic loading. Ninety-two percent of the fractured implants were in reduced diameters (diameter 3.25 mm). These diameter-reduced implants cannot be recommended for clinical use. The cracks were located in 10 of 13 fractured implants at the level of the first turn of the threads, and it was indicated that zirconia implants used in this study osseointegrated well.³⁵ Kohal et al²⁷ also investigated that biomechanical requirements of zirconia implants restored with different all-ceramic crowns for clinical use. All-ceramic crowns were cemented on zirconia implants and exposed to the artificial mouth. The fracture strength of the all-ceramic

implant crown systems was evaluated. Conventional titanium implants restored with porcelain-fused-to-metal crowns served as control group. It was demonstrated that zirconia implants restored with the crowns possibly achieve the biomechanical requirements for anterior teeth.²⁷

ZIRCONIA ORAL IMPLANT SYSTEMS

Zirconia oral implants have been used for several years.⁵⁹ Immediate, non-submerged, root-analogue, anatomic zirconia implants can be custom-made and used in selected cases.^{61,62} The surface treatments for zirconia implants can be machined,¹² mechanically ground,³ nano technology surface modified (CaP nanolayer),⁶³ bioactive ceramic coated (calcium phosphate, bisphosphonate and collagen),^{3,40} acid etched,^{3,49} and sandblasted.⁴⁹

Currently, 9 Y-TZP zirconia implant systems are commercially available: (1) the SIGMA (Incermed, Lausanne, Switzerland) with various Sigma implant designs, (2) the Z-Systems (Oensingen, Switzerland) with its Z-Look3 implant, (3) the Bredent (Bredent Medical, Senden, Germany) with the White Sky implant system, (4) the Ziterion with one-piece the Zit-Z and two-piece Zit-vario (Ziterion, Uffenheim, Germany), (5) the RelImplant system (RelImplant, Hagen, Germany), (6) the Goei system (Goei Inc, Akutsu-Hiroshima, Japan), (7) the Konus system (Konus Dental, Bingen, Germany), (8) the CeraRoot System (Oral Iceberg, Granollers, Barcelona, Spain) with the Ceraroot's one-piece zirconia implant system,^{34,40} and (9) the Zeramax implant system (Dentalpoint AG Swiss Implant Solutions, Zurich, Switzerland).

Zirconia implants can be manufactured as one-piece or two-piece designs.^{3,5,34,59} One-piece systems are in one part, inserted during the surgery. The transmucosal part of one-piece implants is integrated with the implant. Two-piece systems are submerged during the first surgery, and the transmucosal part is connected to the implant during second surgical procedure.⁶⁴

One-piece zirconia implants

Using one-piece implants for everyday practice provides flapless surgery with minimal surgical invasion and benefits soft tissue preservation.⁷ Especially in the anterior region, one-piece implants must be placed at perfect anatomical position to

establish aesthetic appearance of the restoration.⁴² One minor surgery—placing healing caps—can be avoided, so it is unnecessary to wait for the healing of the soft tissue after the second surgery.⁶⁵ The treatment time can be shortened.⁶⁵ Therefore, no clinical data were found for bone augmentation or guided bone regeneration procedure with one-piece implants.^{42,64}

The location of the margin of the one-piece implant supported prosthetic restoration can be defined by intraoral preparation.⁴² However, it has been reported that grinding Y-TZP ceramic can effect monoclinic phase transformation and introduce microcracks that negatively influence the mechanical properties.^{34,42} Andreiotelli and Kohal⁷ reported that in vitro preparation of zirconia implants has a statistically significant negative influence on the fracture strength of the implants. Furthermore, screw joint complications are avoided with one-piece implants. Repair of the fractured implant is not possible when the implant head is fractured.⁷ Another benefit of one-piece implant design is that the implant can be inserted and immediately restored with a provisional crown,⁷ which may effect the patient positively.

Two-piece zirconia implants

Two-piece zirconia implants are preferable when optimal implant stability is not achieved at the implant placement. Bone augmentation procedures can be used with the two-piece implants.^{42,65} The bone-implant interface is important for modeling and remodeling of bone. Movements in bone-implant interface after implantation may affect the early remodeling and osseointegration.^{66,67} Transmitting unwanted loading forces to the healing bone can be minimized with the use of two-piece implants.⁶⁵ Two-stage procedure minimizes the risk of infection because the implant is submerged and peri-implant tissue is separated from the oral microbial environment.⁶⁴

The biomechanical information on two-piece zirconia implants is limited to one in vitro study.⁶⁷ In this study, Kohal et al⁵⁹ evaluated the stability of prototype two-piece zirconia and titanium implants after artificial aging. The results showed that biomechanical stability of all tested implant groups was borderline for clinical use. A high number of failures occurred during the artificial loading in the titanium group at the abutment screw level, and

the zirconia implant groups showed irreparable implant head fractures at low fracture load. In an animal study, Kohal et al⁵⁰ investigated the osseointegration of the loaded custom-made two-piece zirconia and titanium implants. The results demonstrated that there was not any statistically significant difference between the 2 types of implants, and the custom-made zirconia implants showed the same peri-implant soft tissue dimensions.

The purpose of this article is to give information about the dental zirconia implants and present 3 cases treated with two-piece zirconia implants located in the anterior maxillary region.

CLINICAL APPLICATIONS

The patients in this article were referred to the Department of Prosthetic Dentistry at Gazi University, Faculty of Dentistry. After clinical and radiographic examinations, zirconia implants were decided to be inserted because of the esthetic expectations of the patients. Oral and written explanations of the treatment—including risks, benefits, and alternative therapies—were provided. The patients volunteered for this treatment and signed an informed consent form based on the Helsinki Declaration, revised in 2008.

Cylindrical screw type subgingival, platform-switched two-piece zirconia implants (Zit-vario; Ziterion), 4.0 mm diameter and 11.5 mm in length, were inserted into maxillary incisor region. Implant surgery was performed by the same surgeon.

The implant surgical procedures were performed with local anesthesia (Ultracain DS Forte, Aventis, Istanbul, Turkey). The zirconia implants were left in place for 6 months to osseointegrate. During this period, the patients presented wearing an interim removable prosthesis, replacing the missing dentition. The patients were seen 15 days postsurgery, and sutures were removed.

After a 6-month healing period, panoramic and periapical radiographs were obtained and examined for bone-implant osseointegration. The implants were uncovered, the cover caps were removed, and the suitable abutments were chosen. The abutments were cemented into the implant with a self-adhesive universal composite cement (RelyX Unicem, 3M ESPE, Seefeld, Germany), recommended by the abutment manufacturer. Excess cement was

pressed out and removed from the implant-abutment interface. During the soft tissue healing period, the patients presented wearing a provisional fixed prosthesis, replacing the missing dentition. After a 2-week healing period of the soft tissue, an elastomeric impression material (Zeta Plus, Zhermack, Badia Polesine, Italy) was used to take the impression. After the milled zirconia frameworks try-in, definitive restorations were cemented on the implant using self-adhesive universal composite cement (RelyX Unicem, 3M ESPE). The restorations were left out of occlusion, and contacts in lateral excursions were avoided. After setting of the cement, any remnants were removed. The patients received oral hygiene maintenance instructions.

Case 1

A 23-year-old man was referred to our clinic with an endodontical failure of his maxillary left lateral incisor (Figure 1). Because of the patient's esthetic expectations, a zirconia implant was chosen to be inserted. The implant site prepared for the implantation, and it was examined for bone fenestrations or dehiscences after site preparation. A bone defect was observed on the buccal region. The buccal defect area was filled with a xenogeneous bone graft (Bio-Oss, Geistlich Biomaterials, Wolhusen, Switzerland). Abutment connection was performed 6 months following implant insertion. The values of the plaque control record (PCR), bleeding on probing (BOP), and probing depth (PD) were measured after the cementation of definitive restoration and a 1-year follow-up period (Figure 2). The PCR, BOP, and PD values were compared, and the marginal bone level was evaluated by taking standardized periapical radiographs. Peri-implant marginal bone loss was observed on the mesial crestal area at the end of a 1-year follow-up period (Figure 3).

Case 2

A 43-year-old woman with a missing left central maxillary tooth was referred to our clinic (Figure 4). In spite of routine treatment, a two-piece zirconia implant was placed into the maxillary anterior region. The implant was uncovered, and the abutment was connected 6 months following implant insertion. The planning abutments were used for choosing the suitable abutment. An aesthetic and functional result was achieved with the zirconia crown (Figures 5 and



FIGURES 1–6. **FIGURE 1.** Preoperative view of case 1. **FIGURE 2.** View of cemented restoration of case 1 after 12 months. **FIGURE 3.** Periapical radiograph of cemented restoration of case 1 after 12 months. **FIGURE 4.** Preoperative view of case 2. **FIGURE 5.** Cemented restoration of case 2. **FIGURE 6.** Periapical radiograph of cemented restoration of case 2.

6). Peri-implant lesion, soft-tissue recession, or prosthetic complications were not observed after a 1 month follow-up period.

Case 3

A 25-year-old woman with a missing right central tooth that had been fractured in a traffic accident (Figure 7) was referred to our clinic. The periapical radiography showed no apical lucency in the area of the missing tooth (Figure 8). A two-piece zirconia implant was placed into the maxillary anterior region. After a 6-month osseointegration period (Figure 9), a 15 degree angled zirconia abutment was chosen, prepared, and cemented onto the implant (Figure 10). After using a provisional crown for 2 weeks, a definitive zirconia crown was made and cemented (Figures 11 and 12). The patient was satisfied with the aesthetic and functional results.

DISCUSSION

Investigations suggest that zirconia ceramics are highly biocompatible and have sufficient mechanical properties to be used as dental implant base material.* Careful case selection is very important

when using zirconia implants. To achieve successful aesthetic results with implant supported restorations in the esthetic zone, advance planning for accurate and adequate placement of the implants is a requirement.^{68–72} In addition to high mechanical properties of the zirconia implants, long-term clinical studies must be performed for clinical acceptability and consideration as an alternative to titanium implants. Clinical studies with zirconia implants is very limited; only a few one-piece^{3,5,36,68–70,72} and 2 two-piece zirconia implant^{71,73} case reports have been published.

The clinical investigations and case reports related with zirconia implants started in the last decade. In 2004, Kohal et al⁷¹ presented the first two-piece zirconia implant case report. A custom-made zirconia implant was inserted in the patient and after a 6-month healing period, the single all-ceramic crown was cemented onto the implant. It was demonstrated that zirconia implants would be offered for an esthetic restoration of missing teeth.⁷¹

In 2006, Mellinghoff³⁶ reported the clinical results of zirconia implants. In this study, 189 implants were inserted in 71 patients and examined. The 1-year survival rate of the implants was 93%. In another 1-year follow-up study, 100 one-piece zirconia dental implants were investigated in

*References 1, 2, 6, 12, 27, 29, 34, 35, 39, 45, 58, 59.



FIGURES 7–12. **FIGURE 7.** Preoperative view of case 3. **FIGURE 8.** Preoperative periapical radiograph of case 3. **FIGURE 9.** Periapical radiograph of case 3 after 6 months. **FIGURE 10.** Cemented abutment of case 3. **FIGURE 11.** View of the cemented restoration of case 3. **FIGURE 12.** Periapical radiograph of cemented restoration of case 3.

humans with 2 different rough surfaces by Oliva et al.⁵ The overall implant success rate after 1 year of follow-up was 98%.⁵

Oliva et al,⁶⁸ Siiraalta et al,⁶⁹ and Aydın et al⁷⁰ presented aesthetic replacement of the maxillary incisors and presented a maxillary anterior partially edentulous space restored with one-piece zirconia implants. The patients functioned successfully with their prostheses and were satisfied with the final results. In another clinical report, Oliva et al⁷² demonstrated the usage of zirconia oral implants in a titanium allergy patient. Full-mouth oral rehabilitation using zirconium oxide dental implants were presented, the patient was satisfied with the prosthesis.⁷² It was reported that zirconia implants can be used in titanium allergy patients.⁷²

In a long-term clinical study, Oliva et al³ investigated the success of one-piece zirconia implants. A 5-year success rate of 831 zirconia dental implants were evaluated in humans. One-piece zirconia dental implants with 3 different roughened surfaces were designed and manufac-

ured for this study: coated, uncoated, and acid etched. The success rate of the acid-etched surface group was significantly better than the other groups. The results showed that the overall implant success rate after 5 years of follow-up was 95%.

Further, in 2011, Nevins et al⁷³ reported the histological and clinical evaluations of a two-piece zirconia implants and compared them with the titanium implants. Four titanium and 2 zirconia implants were placed in a healthy woman. One two-piece zirconia implant was displaced for biopsy after 6 months. Clinical and radiographic observations showed that both zirconia and titanium implants achieved osseointegration. Gingival tissues were healthy, and excellent vertical bone height was demonstrated in the radiographs. Histologic observations demonstrated that the bone-to-implant contact with a zirconia implant surface was sufficient to provide clinical and histologic evidence of osseointegration. It was concluded that zirconia implants provided appropriate conditions for soft and hard tissue healing.⁷³

The purpose of this article is to give information about zirconia oral implants and to present cases treated with two-piece zirconia implants, but only short-term success of a new two-piece zirconia implant was evaluated. Using zirconia implants can be offered for esthetic restorations of anterior missing teeth, but investigations focusing on the long-term clinical success rate of zirconia implants are necessary.

CONCLUSIONS

Based on the review of literature, it is concluded that zirconia implant systems are a new addition in implant dentistry and may become an alternative to titanium with more natural color. Cases in this article presented a two-piece zirconia implant located in anterior maxillary region. In short-term evaluation, the radiographic and clinical outcomes were successful, and the patients were satisfied with the final result; however, to properly evaluate the two-piece implant's clinical performance and recommend them for routine clinical use, well-planned controlled animal investigations and clinical trials must be performed with a long-term follow-up.

REFERENCES

1. Depprich R, Zipprich H, Ommerborn M, et al. Osseointegration of zirconia implants compared with titanium: an in vivo study. *Head Face Med.* 2008;4:1–8.
2. Hoffmann O, Angelov N, Gallez F, Jung RE, Weber FE. The zirconia implant-bone interface: a preliminary histologic evaluation in rabbits. *Int J Oral Maxillofac Implants.* 2008;23:691–695.
3. Oliva J, Oliva X, Oliva JD. Five-year success rate of 831 consecutively placed Zirconia dental implants in humans: a comparison of three different rough surfaces. *Int J Oral Maxillofac Implants.* 2010;25:336–344.
4. Albrektson T, Sennerby L, Wennerberg A. State of the art of oral implants. *Periodontol 2000.* 2008;47:15–26.
5. Oliva J, Oliva X, Oliva JD. One-year follow-up of first consecutive 100 zirconia dental implants in humans: a comparison of 2 different rough surfaces. *Int J Oral Maxillofac Implants.* 2007;22:430–435.
6. Silva NR, Coelho PG, Fernandes CA, Navarro JM, Dias RA, Thompson VP. Reliability of one-piece ceramic implant. *J Biomed Mater Res B Appl Biomater.* 2009;88:419–426.
7. Andreiotelli M, Kohal RJ. Fracture strength of zirconia implants after artificial aging. *Clin Implant Dent Relat Res.* 2009;11:158–166.
8. Heydecke G, Kohal R, Glaser R. Optimal esthetics in single tooth replacement with the Re-Implant system: a case report. *Int J Prosthodont.* 1999;12:184–189.
9. Bianco PD, Ducheyne P, Cuckler JM. Local accumulation of titanium released from a titanium implant in the absence of wear. *J Biomed Mater Res.* 1996;31:227–234.
10. Weingart D, Steinemann S, Schilli W, et al. Titanium

deposition in regional lymph nodes after insertion of titanium screw implants in maxillofacial region. *Int J Oral Maxillofac Surg.* 1994;23:450–452.

11. Tschernitschek H, Borchers L, Geurtsen W. Nonalloyed titanium as a bioinert metal – a review. *Quintessence Int.* 2005;36:523–530.
12. Kohal RJ, Wolkewitz M, Hinze M, Han JS, Bächle M, Butz F. Biomechanical and histological behavior of zirconia implants: an experiment in the rat. *Clin Oral Implants Res.* 2009;20:333–339.
13. Andreiotelli M, Wenz HJ, Kohal RJ. Are ceramic implants a viable alternative to titanium implants? A systematic literature review. *Clin Oral Implants Res.* 2009;20(suppl 4):32–47.
14. Sandhaus S. The Cerasand endosseous implant. *Actual Odontostomatol.* 1987;41(160 Spec No):607–626.
15. Sandhaus S. Technic and instrumentation of the implant C.B.S. (crystalline bone screw) [in Italian]. *Informatore Odontostomatologico.* 1968;4:19–24.
16. Schulte W. The intraosseous Al₂O₃ (Frialit) Tübingen implant. Developmental status after eight years (1–3). *Quintessence Int.* 1984;154:1–39.
17. Schulte W, d'Hoedt B. 13 years of the Tübingen implant system made by Frialit. Additional results [in German]. *Z Zahnärztl. Implantol.* 1988;3:167–172.
18. Schulte W, Heimke A. The Tübingen immediate implant [in German]. *Quintessenz.* 1976;27:17–23.
19. Schulte W, Kleineikenscheidt H, Lindner K, Schareyka R. The Tübingen immediate implant in clinical studies [in German]. *Dtsch Zahnärztl Z.* 1978;33:348–359.
20. Schulte W, Kleineikenscheidt H, Lindner K, et al. Animal experiments on the question of healing around the Tübingen immediate implant [in German]. *Dtsch Zahnärztl Z.* 1978;33:326–331.
21. Müller W, Piesold J, Glien W. Stomatol DDR. Properties and clinical application of dental implants of Bionit aluminium oxide ceramic [in German]. *Stomatol DDR.* 1988;38:673–678.
22. Piesold JU, Müller W. Tooth replacement by BIONIT-implants [in German]. *Dtsch Stomatol.* 1991;41:128–132.
23. Brinkmann EL. Ceramic anchor implant as a bridge-end abutment (Brinkmann's Class II) – report of 10 years' experience in clinical use [in German]. *Quintessenz.* 1987;38:811–818.
24. Koth DL, McKinney RV Jr, Davis QB. The single-crystal sapphire endosteal dental implant. A longitudinal human study: one-year results. *J Prosthet Dent.* 1983;50:72–80.
25. Akagawa Y, Hashimoto M, Kondo N, Satomi K, Takata T, Tsuru H. Initial bone-implant interfaces of submergible and supramergible endosseous single-crystal sapphire implants. *J Prosthet Dent.* 1986;55:96–100.
26. Gahlert M, Gudehus T, Eichhorn S, Steinhäuser 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;18:662–668.
27. Kohal RJ, Klaus G, Strub JR. Zirconia-implant-supported all-ceramic crowns withstand long-term load: a pilot investigation. *Clin Oral Implants Res.* 2006;17:565–571.
28. 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;88:519–529.
29. Depprich R, Zipprich H, Ommerborn M, et al. Osseointegration of zirconia implants: an SEM observation of the bone-implant interface. *Head Face Med.* 2008;4:1–7.
30. Stadlinger B, Hennig M, Eckelt U, Kuhlisch E, Mai R. Comparison of zirconia and titanium implants after a short healing period. A pilot study in minipigs. *Int J Oral Maxillofac Surg.* 2010;39:585–592.

31. Piconi C, Maccauro G. Zirconia as a ceramic biomaterial. *Biomaterials*. 1999;20:1–25.
32. Piconi C, Maccauro G, Muratori F, Brach Del Prever E. Alumina and zirconia ceramics in joint replacements. *J Appl Biomater Biomech*. 2003;1:19–32.
33. Helmer JD, Driskell TD. Research on bioceramics. Symposium on Use of Ceramics as Surgical Implants, 1969. Clemson University, Clemson, SC.
34. Kohal RJ, Wolkewitz M, Tsakona A. The effects of cyclic loading and preparation on the fracture strength of zirconium-dioxide implants: an in vitro investigation. *Clin Oral Implants Res*. 2011;22:808–814.
35. Gahlert M, Burtscher D, Grunert I, Kniha H, Steinhäuser E. Failure analysis of fractured dental zirconia implants. *Clin Oral Implants Res*. 2012;23:287–293.
36. Mellinshoff J. First clinical results of dental screw implants made of zirconium oxide [in German]. *Z Zahnztl Implantol*. 2006;22:288–293.
37. Kollar A, Huber S, Mericske E, Mericske-Stern R. Zirconia for teeth and implants: a case series. *Int J Periodontics Restorative Dent*. 2008;28:479–487.
38. Sollazzo V, Pezzetti F, Scarano A, et al. Zirconium oxide coating improves implant osseointegration in vivo. *Dent Mater*. 2008;24:357–361.
39. Rocchietta I, Fontana F, Addis A, Schupbach P, Simion M. Surface-modified zirconia implants: tissue response in rabbits. *Clin Oral Implants Res*. 2009;20:844–850.
40. Özkurt Z, Kazazoğlu E. Zirconia dental implants: a literature review. *J Oral Implantol*. 2011;37:367–376.
41. Sennerby L, Dasmah A, Larsson B, Iverhed M. Bone tissue responses to surface-modified zirconia implants: a histomorphometric and removal torque study in the rabbit. *Clin Implant Dent Relat Res*. 2005;7(suppl 1):S13–S20.
42. Wenz HJ, Bartsch J, Wolfart S, Kern M. Osseointegration and clinical success of zirconia dental implants: a systematic review. *Int J Prosthodont*. 2008;21:27–36.
43. Tanaka K, Tamura J, Kawanabe K, et al. Phase stability after aging and its influence on pin-on-disk wear properties of Ce-TZP/Al₂O₃ nanocomposite and conventional Y-TZP. *J Biomed Mater Res A*. 2003;67:200–207.
44. Ban S, Sato H, Suehiro Y, Nakanishi H, Nawa M. Biaxial flexure strength and low temperature degradation of Ce-TZP/Al₂O₃ nanocomposite and Y-TZP as dental restoratives. *J Biomed Mater Res B Appl Biomater*. 2008;87:492–498.
45. Fischer J, Stawarczyk B, Trottman A, Hämmerle CH. Impact of thermal properties of veneering ceramics on the fracture load of layered Ce-TZP/A nanocomposite frameworks. *Dent Mater*. 2009;25:326–330.
46. Warashina H, Sakano S, Kitamura S, et al. Biological reaction to alumina, zirconia, titanium and polyethylene particles implanted onto murine calvaria. *Biomaterials*. 2003;24:3655–3661.
47. Degidi M, Artese L, Scarano A, et al. Inflammatory infiltrate, microvessel density, nitric oxide synthase expression, vascular endothelial growth factor expression, and proliferative activity in peri-implant soft tissues around titanium and zirconium oxide healing caps. *J Periodontol*. 2006;77:73–80.
48. Carinci F, Pezzetti F, Volinia S, et al. Zirconium oxide: analysis of MG63 osteoblast-like cell response by means of a microarray technology. *Biomaterials*. 2004;25:215–28.
49. Gahlert M, Röhling S, Wieland M, et al. Osseointegration of zirconia and titanium dental implants: a histological and histomorphometrical study in the maxilla of pigs. *Clin Oral Implants Res*. 2009;20:1247–1253.
50. Kohal RJ, Weng D, Bächle M, Strub JR. Loaded custom-made zirconia and titanium implants show similar osseointegration: an animal experiment. *J Periodontol*. 2004;75:1262–1268.
51. Payer M, Arnetzl V, Kirmeier R, et al. Immediate provisional restoration of single-piece zirconia implants: a prospective case series – results after 24 months of clinical function. *Clin Oral Implants Res*. 2013;24:569–275.
52. Kohal RJ, Knauf M, Larsson B, Sahlin H, Butz F. One-piece zirconia oral implants: one-year results from a prospective cohort study. 1. Single tooth replacement. *J Clin Periodontol*. 2012;39:590–597.
53. Smith DE, Zarb GA. Criteria for success of osseointegrated endosseous implants. *J Prosthet Dent*. 1989;62:567–572.
54. Ostman PO, Hellman M, Sennerby L. Ten years later. Results from a prospective single-centre clinical study on 121 oxidized (TiUnite) Branemark implants in 46 patients. *Clin Implant Dent Relat Res*. 2012;14:852–860.
55. Francetti L, Azzola F, Corbella S, Taschieri S, Del Fabbro M. Evaluation of clinical outcomes and bone loss around titanium implants with oxidized surface: six-year follow-up results from a prospective case series study. *Clin Implant Dent Relat Res*. 2014;16:81–88.
56. Lethaus B, Kälber J, Petrin G, Brandstätter A, Weingart D. Early loading of sandblasted and acid-etched titanium implants in the edentulous mandible: a prospective 5-year study. *Int J Oral Maxillofac Implants*. 2011;26:887–892.
57. Çağlar A, Bal BT, Karakoca S, Aydın C, Yılmaz H, Sarısoy S. Three-dimensional finite element analysis of titanium and yttrium-stabilized zirconium dioxide abutments and implants. *Int J Oral Maxillofac Implants*. 2011;26:961–969.
58. Çağlar A, Bal BT, Aydın C, Yılmaz H, Özkan S. Evaluation of stresses occurring on three different zirconia dental implants: three-dimensional finite element analysis. *Int J Oral Maxillofac Implants*. 2010;25:95–103.
59. Kohal RJ, Finke HC, Klaus G. Stability of prototype two-piece zirconia and titanium implants after artificial aging: an in vitro pilot study. *Clin Implant Dent Relat Res*. 2009;11:323–329.
60. Pirker W, Kocher A. Immediate, non-submerged, root-analogue zirconia implant in single tooth replacement. *Int J Oral Maxillofac Surg*. 2008;37:293–295.
61. Pirker W, Wiedemann D, Lidauer A, Kocher AA. Immediate, single stage, truly anatomic zirconia implant in lower molar replacement: a case report with 2.5 years follow-up. *Int J Oral Maxillofac Surg*. 2011;40:212–216.
62. Pirker W, Kocher A. Immediate, non-submerged, root-analogue zirconia implants placed into single-rooted extraction sockets: 2-year follow-up of a clinical study. *Int J Oral Maxillofac Surg*. 2009;38:1127–1132.
63. Lee J, Sieweke JH, Rodriguez NA, et al. Evaluation of nanotechnology-modified zirconia oral implants: a study in rabbits. *J Clin Periodontol*. 2009;36:610–617.
64. Heydenrijk K, Raghoebar GM, Meijer HJ, Van Der Reijden WA, Van Winkelhoff AJ, Stegenga B. Two-part implants inserted in a one-stage or a two-stage procedure. A prospective comparative study. *J Clin Periodontol*. 2002;29:901–909.
65. Esposito M, Grusovin MG, Chew YS, Coulthard P, Worthington HV. Interventions for replacing missing teeth: 1- versus 2-stage implant placement. *Cochrane Database Syst Rev*. 2009;3:CD006698.
66. Goiato MC, Pellizzer EP, dos Santos DM, et al. Clinical viability of immediate loading of dental implants: part I – factors for success. *J Craniofac Surg*. 2009;20:2139–2142.
67. Salama H, Rose LF, Salama M, Betts NJ. Immediate loading of bilaterally splinted titanium root-form implants in fixed prosthodontics – a technique reexamined: two case reports. *Int J Periodontics Restorative Dent*. 1995;15:344–361.
68. Oliva J, Oliva X, Oliva JD. Zirconia implants and all-ceramic restorations for the esthetic replacement of the maxillary central incisors. *Eur J Esthet Dent*. 2008;3:174–185.

69. Sierraalta M, Razzoog ME. A maxillary anterior partially edentulous space restored with a one-piece zirconia implant fixed partial denture: a clinical report. *J Prosthet Dent.* 2009;101: 354–358.

70. Aydin C, Yilmaz H, Ata SO. Single-tooth zirconia implant located in anterior maxilla. A clinical report. *N Y State Dent J.* 2010; 76:30–33.

71. Kohal RJ, Klaus G. A zirconia implant-crown system: a case report. *Int J Periodontics Restorative Dent.* 2004;24:147–153.

72. Oliva X, Oliva J, Oliva JD. Full-mouth oral rehabilitation in a titanium allergy patient using zirconium oxide dental implants and zirconium oxide restorations. A case report from ongoing clinical study. *Eur J Esthet Dent.* 2010;5:190–203.

73. Nevins M, Camelo M, Nevins ML, Schupbach P, Kim DM. Pilot clinical and histologic evaluations of a two-piece zirconia implant. *Int J Periodontics Restorative Dent.* 2011;31:157–163.