Osseointegration and Clinical Success of Zirconia Dental Implants: A Systematic Review

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Purpose: Various ceramic implant systems made of yttria–stabilized tetragonal zirconia polycrystals (Y-TZP) have become commercially available in recent years. A systematic search of the literature was performed to assess the clinical success of dental Y-TZP implants and whether the osseointegration of Y-TZP is comparable to that of titanium, the standard implant material. ***Materials and Methods:*** The internet database MEDPILOT was searched cumulatively for the keywords *zircon** and *dent** and implant as well as for *zircon** and *osseointegration.* The last search was conducted on January 31st, 2007. Subsequently, the reference lists of the relevant publications were searched. Furthermore, a letter was sent to the 5 identified manufacturers of zirconia dental implants to ask for peer-reviewed publications. ***Results:*** Ninety-six articles were found by the search strategy. No controlled clinical studies in humans regarding clinical outcomes or osseointegration could be identified. Clinical data were restricted to case studies and case series. Only 7 animal studies fulfilled the inclusion criteria. Osseointegration was evaluated at 4 weeks to 24 months after placement in different animal models and sites and under different loading conditions. The mean bone-implant contact percentage was above 60% in almost all experimental groups. In studies that used titanium implants as a control, Y-TZP implants were comparable to or even better than titanium implants. Surface modifications may further improve initial bone healing and resistance to removal torque. ***Conclusions:*** Y-TZP implants may have the potential to become an alternative to titanium implants but cannot currently be recommended for routine clinical use, as no long-term clinical data are available. *Int J Prosthodont 2008;21:27–36.*

Commercially pure titanium has been used for more than 30 years and is still the material of choice for dental intraosseous implants. Titanium dental implants with either smooth or roughened surfaces have shown high success rates in various indications.[1–3] The esthetic outcome of restorations supported by titanium implants might be compromised if the dark color of the implant shines through a thin peri-implant mucosa or if the implant head becomes visible following soft tissue recession. Furthermore, some authors see a potential health hazard in titanium particles or possible corrosive products.[4,5] Increased concentrations of titanium have been detected in tissues close to implant surfaces[6] and in regional lymph nodes.[7] Although the clinical relevance of these findings is not yet clear, an increasing number of patients are asking for metal-free treatment options.

Tooth-colored ceramics were considered early as alternative implant materials. A pioneer in the development of ceramic dental implants, S. Sandhaus, described a ceramic dental implant system—the crystalline bone screw—more than 35 years ago[8] and was further involved in the progress of ceramic implants.[9] But important biomechanical characteristics of ceramic

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implants such as fracture toughness were inferior to those of titanium. In the 1980s, an implant made of aluminum oxide (Al_2O_3), the Tübinger Immediate Implant, was used, but it was later withdrawn from the market because of its high clinical fracture rate.[10,11] Other investigations using different Al_2O_3 implant systems found less bone-implant contact compared to titanium[12] and reduced survival rates.[13,14]

Yttria–stabilized tetragonal zirconia polycrystal (Y-TZP) exhibits a very high flexural strength (900 to 1,200 MPa), a favorable fracture toughness (K_{IC} 7 to 10 $MPam^{-1}$), and a suitable Young's modulus (210 GPa)[15] and thus has the potential to become the ceramic material of choice for dental implants. Y-TZP has been used extensively in orthopedic surgery as a material for ball heads in total hip replacement since its introduction in the 1980s.[16] (Two different abbreviations are used in the literature for yttria-stabilized zirconia: Y-TZP and Y-PSZ [yttria–partially stabilized zirconia]. In this article, the abbreviation Y-TZP is used, since yttria-stabilized zirconia in dentistry usually consists completely of tetragonal zirconia polycrystals, while Y-PSZ may also contain fractions of the monoclinic or cubic phase.)

In dentistry, Y-TZP was successfully introduced as a material for frameworks in all-ceramic fixed partial denture restorations and for all-ceramic abutments for dental implants.[17–19] However, little information is available on the mechanical strength of Y-TZP implants and Y-TZP implant–supported restorations. In an investigation using 3-dimensional finite element analysis, Y-TZP implants showed very similar stress distribution compared with titanium implants of the same size and shape.[20] In another study, Kohal et al[21] tested in vitro whether Y-TZP implants restored with different all-ceramic crowns would meet the biomechanical requirements for clinical use. Titanium implants restored with porcelain-fused-to-metal crowns served as controls. The authors concluded that Y-TZP implants restored with Procera crowns (Nobel Biocare) could possibly fulfill the biomechanical requirements for anterior teeth. The use of low-strength Empress-I crowns (Ivoclar Vivadent) on Y-TZP implants was questioned, as crack propagation was observed in the loading area and artificial loading significantly decreased the fracture strength of these crowns.

Zirconia as a Biomaterial

The high resistance of partially stabilized zirconia against crack propagation is based on a phase transformation from the tetragonal to the monoclinic phase, which leads to a volume expansion of approximately 3% to 4% and was described by Garvie et al in 1975.[22] The energy associated with crack propagation is depleted in the phase transformation and in overcoming the compression stresses caused by volume expansion. For Y-TZP ceramic, these results were first reported by Rieth et al[23] and Gupta et al.[24] Y-TZP materials containing 2% to 3% mol yttrium oxide (Y_2O_3) are composed entirely of tetragonal grains with sizes in the order of hundreds of nanometers. The fraction of the tetragonal phase retained at room temperature, and subsequently the material's mechanical properties, are dependent on the size of the grains, on the yttrium oxide content, and on the grade of constraint exerted on them by the matrix.[15] Fully stabilized zirconia (> 8% mol Y_2O_3) forms a stable cubic-phase solid solution from room temperature up to 2,500°C and is not suitable for dental applications.

Since Y-TZP has been used in orthopedic surgery for more than 30 years, its biologic safety has been thoroughly investigated. Because it is mainly used for femoral ball heads in total hip replacement and therefore contacts soft tissues and blood in vivo, most authors tested Y-TZP with fibroblasts or blood cells. Biocompatibility has been evaluated using in vitro tests performed on different materials (eg, powders or compacts, different impurity levels) with different cell lines in different biologic conditions (eg, fibroblasts, phytohemagglutinin-stimulated lymphocytes), with similar positive results.[15,25] Furthermore, in vitro carcinogenicity[26] and mutagenicity[27] tests showed negative results. Interestingly, in vivo investigations concerned with the biocompatibility of the "would-be biomaterial" zirconia were performed as early as 1969—many years before the first in vitro investigations.[15] Biocompatibility was evaluated mainly by using alumina as a reference material for a "bio-inert" ceramic.[28–34] The quality of the bone-implant contact was comparable to that of alumina implants[32,33] and was influenced by implantation site[28] and implant surface modifications.[34] In a comprehensive review on zirconia ceramic, Picconi and Maccauro[15] stated that there is general agreement on the absence of local or systemic toxic effects after the implantation of zirconia ceramics into muscles or bones of different animals or after powder injection in mice.

Because significant concentrations of radioactive elements are present in the raw material used to fabricate zirconia powder, possible radioactive exposure resulting from zirconia implants has been discussed.[35] Radiation protection aspects linked to the handling of huge quantities of zircon-bearing materials, eg, zircon sands, are well known to people concerned with the safety of industrial workers in this field.[36] Because radioactive exposure is not caused by the zirconia itself but by impurities, the purification process of precursors of Y-TZP must be controlled carefully.[37]

The Problem of Low-Temperature Degradation

Because the comprehensive clinical experience with biomedical grade zirconia ceramic in the field of orthopedic surgery is often quoted to support the use of the same material in dentistry, an event should be noticed that dramatically changed the usage of zirconia femoral heads. It is well known that because of the metastability of the tetragonal phase at room temperature, Y-TZP is prone to aging in the presence of water.[38] This potential hazard seemed to be very limited under in vivo conditions until the year 2001, when about 400 femoral heads failed in a very short time period.[39] The failures were linked to the accelerated aging of two batches of the Prozyr femoral head following a change in the processing technique. These events generated a need for further studies to better understand the process of in vitro and in vivo aging of Y-TZP.

Low-temperature degradation occurs via a slow surface transformation from the metastable tetragonal phase to the stable monoclinic phase in the presence of water or water vapor. The transformation process occurs by a nucleation and growth process, which is highly related to the quality of various process stages that will influence the microstructure of Y-TZP. Additionally, aging kinetics will be influenced by the surface state of the Y-TZP specimen.[40] According to Chevalier,[39] a modification of ISO standard 13356[41] is advised to ensure the quality of biomedical-grade zirconia ceramic. Papanagiotou et al[42] investigated the effect of different aging and finishing procedures on Y-TZP bars. No negative effects on flexural strength were detected, but boiling in water or storing in humidified air at 250°C for up to 7 days led to monoclinic phase transformation on the material surface. Additionally, the yttria concentration on specimen surfaces that were boiled for 7 days was reduced. The authors concluded that the long-term clinical serviceability of the Y-TZP ceramic might be compromised by these effects. This concern is shared by Tinschert et al,[43] who found that some zirconia ceramics had a high susceptibility to subcritical crack growth in a moist environment.

Aim of the Review

To the knowledge of the authors, there are currently 5 different commercially available Y-TZP dental implant systems: SIGMA (Incermed), Z-Systems, Bredent-Zirkon, Ziterion, and CeraRoot. Some case reports have been published locally,[44–47] but only one was published in the indexed literature,[48] and there seems to be a large discrepancy between the increasing use of Y-TZP implants in patients and the scientific basis for the predictability of this treatment option, especially with regard to osseointegration and the long-term clinical success of Y-TZP implants and their prosthetic components. Thus, it was the aim of this review to answer the following questions:

1. Is the osseointegration of dental Y-TZP implants comparable to that of dental titanium implants, especially with regard to bone-implant contact?
2. Are valid scientific data on the clinical success of dental Y-TZP implants as defined by Zarb and Albrektsson[49] available, and if so, over what time periods?

Materials and Methods

The internet database MEDPILOT (www.medpilot.de), which includes PubMed and 15 additional databases, was used to search cumulatively for the keywords *zircon** and *dent** and *implant* as well as for *zircon** and *osseointegration*. No language restriction was applied. The last electronic search was conducted on January 31st, 2007. Screening of eligible studies and quality assessment were conducted in duplicate. Subsequently, the reference lists of the relevant publications were searched.

Furthermore, in November 2006, a letter was sent to the 5 identified manufacturers of zirconia dental implants with the following 4 questions:

1. Do you have peer-reviewed scientific publications concerning the clinical success of your zirconia ceramic implant in humans?
2. Do you have peer-reviewed scientific publications concerning the osseointegration of your zirconia implant system in animals or humans?
3. Do you have ongoing unpublished studies concerning the above subjects 1 and 2 with a confirmed date of publication, ie, articles that are in press?
4. How many implants has your company sold since they were introduced to the market?

All publications found were entered into a reference database (EndNote, Version 9, Thomson ResearchSoft). For further evaluation, the following inclusion criteria were defined: Only clinical or animal studies investigating osseointegration or clinical success of Y-TZP dental implants were included. Studies of ceramic composites or of ZrO_2 coatings on metallic implants were not considered. Also, studies using cell culture models or investigating soft tissue responses to zirconia were not included. Publication had to reach evidence level III (well-designed nonexperimental descriptive studies) or higher.[50] Case studies and case series were not included.

If data from relevant studies had been published in different journals, only the most significant publication was considered. The publications were sorted into clinical studies, animal studies with loaded implants, and animal studies with unloaded implants.

Results

Literature Search

In all, 96 articles were found by the electronic search. No controlled clinical study in humans regarding the clinical outcome of zirconia ceramic implants or osseointegration could be identified. Only 7 animal studies fulfilled the inclusion criteria: One included study investigated the osseointegration of titanium and Y-TZP as a post material in apicectomy[51]; because these posts had bone contact, the study was included in the review. The 2 identified clinical studies[52,53] were not included because they did not reach evidence level III; these will be addressed in the discussion. No further articles that fulfilled the inclusion criteria could be identified by a secondary search in the reference lists.

Questionnaire

Only 2 of the 5 identified manufacturers (Z-Systems and Ziterion) responded to the short questionnaire. Neither could provide further information on any peer-reviewed studies already published or with a confirmed date of publication. The Z-Lock implant (Z-Systems) was introduced in 2004 (number of implant units sold: 7,600), and the zit-z implant (Ziterion) was introduced in 2006 (number of implant units sold: not provided).

Animal Studies of Unloaded Implants

Four studies that assessed unloaded Y-TZP dental implants in animals met inclusion criteria. In the first, Dubruille et al[54] evaluated the quality of the tissue-implant interface of implants that were placed into mandibular bone of dogs that had been previously filled with animal-originated calcium carbonate (Biocoral 450, Inoteb). After 6 months, 6 Y-TZP implants, 6 alumina implants, and 6 titanium implants were inserted and allowed to heal submerged for 10 months. No significant differences between the implant materials were found in macroscopic, radiographic, and microscopic examinations. The authors evaluated the bone-implant contact in the cervical, central, and apical regions and found higher values in the cervical region (85% to 89%) than in the central (44% to 72%) and apical regions (29% to 45%). The overall mean implant-bone contact values were 64.6% ± 12.7% for the Y-TZP implants, 68% ± 13.9% for the alumina implants, and 54% ± 12.9% for the titanium implants (Table 1).

Schultze-Mosgau et al[51] investigated the osseointegration of Y-TZP cones and titanium cones with regard to their application for apicectomy. Twenty zirconia cones (Friadent) and 20 titanium cones (Straumann) were inserted in the mandibles of 4 minipigs and removed en bloc after 6 months. Bone-implant contact and bone–fibrous connective tissue contact were quantified and their ratio was calculated. For both implant materials, light microscopy and fluorescence microscopy revealed no differences in the morphology and dynamics of bone healing. In the quantitative analysis, a significantly higher ratio was found for Y-TZP (1.47 ± 1.12) than for titanium (0.97 ± 1.10), indicating better bone healing on the zirconia surface after 6 months in the chosen experimental design (Table 1).

Scarano et al[55] analyzed the bone response to Y-TZP implants inserted in the tibiae of rabbits. Five rabbits received a total of 20 Y-TZP implants, which were retrieved en bloc after 4 weeks of healing. The implants were made of Y-TZP ceramic (Norton Desmarquest), passivated according to ASTM A380, and cleaned with water, alcohol rinsing, and ultrasonic methods. The form and dimensions of the implant were illustrated only with radiographs and photographs; no details were provided. According to the authors, all implants appeared to be osseointegrated without signs of inflammation or mobility. The formation of osteoid directly on the implant surface was observed, and a mean bone-implant contact of 68.4% ± 2.4% was calculated (Table 1). The authors concluded that the investigated Y-TZP implants are highly biocompatible and osteoinductive.

In a rabbit model, Sennerby et al[56] investigated histologically and biomechanically the bone tissue response to Y-TZP implants with 2 different surface modifications (Zr-A and Zr-B) and compared this with the tissue response to machined (unmodified) Y-TZP implants (Zr-Ctr) and oxidized titanium implants (modified TiUnite implants, Nobel Biocare). Mean surface roughness was highest for the titanium (R_a = 1.30 µm) and the Zr-A implants (R_a = 1.24 µm), followed by the Zr-B (R_a = 0.93 µm) and finally the Z-Ctr implants (R_a = 0.75 µm). Twelve rabbits received 96 implants (2 in each tibia and 2 in each femur). After a healing period of 6 weeks, the implants were either subjected to removal torque tests or removed en bloc to analyze the bone-implant contact. The removal torque values were significantly higher for the surface-modified zirconia implants and the titanium implants compared to the zirconia implants with the machined surface (Table 1). Evaluation of the quantitative

Table 1 Animal Studies of Unloaded Y-TZP Implants

Study	Implant design	Surface treatment	Surgical protocol	Success criteria, results
Dubruille et al (1999)[54] (5 dogs, 18 implants)				Bone-implant contact
Y-TZP (6 implants)	Sigma (Incermed); no further information	No information	Mandibular sockets filled after extraction with Coral 450; insertion after 6 mo, healing for 10 mo	65%
Control: Al_2O_3 (6 implants)	Cerasand (Incermed); no further information	No information	Same protocol	68%
Control: titanium grade I (6 implants)	Manufactured from titanium wire, same dimensions as other groups	Machined, ultrasonically cleaned, dry heat sterilized	Same protocol	54%
Schultze-Mosgau et al (2000)[51] (4 minipigs, 40 implants)				Ratio between implant/bone contact and implant/connective tissue contact
Y-TZP (20 implants)	Y-PSZ cone (Friadent), diameter 1.4 mm, length 7 mm	No information	Inserted in the mandible; healing for 6 mo	1.47
Control: titanium (20 implants)	Titanium cone (Straumann), diameter 1.4 mm, length 6.5 mm	No information	Same protocol	0.91
Scarano et al (2003)[55] (5 rabbits, 20 implants)				
Y-TZP; no control	Experimental (Norton Desmarquest), no detailed information given (only radiographs, photographs)	Passivation (ASTM A380), different cleaning steps	Inserted in the tibia; healing for 4 wk	Bone-implant contact: 68%
Sennerby et al (2004)[56] (12 rabbits, 96 implants)				Bone-implant contact,* removal torque values*
Y-TZP (24 implants)	Experimental screw type, diameter 3.75 mm, length 9mm (threaded part 6mm)	Machined presintered, then sintered to full density	Placed in femur and tibia; healing for 6 wk	BIC: femur, 46%; tibia (3 best), 36% RTV: femur, 20 Ncm; tibia, 12 Ncm
Y-TZP (24 implants)	Same design	Machined presintered, then surface roughened by sintering to full density using pore-former A	Same protocol	BIC: femur, 60%; tibia (3 best), 56% RTV: femur, 98 Ncm; tibia, 47 Ncm
Y-TZP (24 implants)	Same design	Machined presintered, then surface roughened by sintering to full density using pore-former B	Same protocol	BIC: femur, 70%; tibia (3 best), 47% RTV: femur, 85 Ncm; tibia, 58 Ncm
Control: titanium (24 implants)	Screw type (Nobel Biocare), diameter 3.75 mm, length ~7.5 mm (threaded part 6 mm)	TiUnite (Nobel Biocare)	Same protocol	BIC: femur, 68%; tibia (3 best), 47% RTV: femur, 74 Ncm; tibia, 42 Ncm

*Values not given in the text; assumption from figures.

measurement of the bone-implant contact ratio showed no significant differences between the 4 tested implants. However, the 3 best threads at the tibia site were compared, the modified Zr-A implants performed significantly better than the machined Z-Ctr implants. Qualitatively, the authors found signs of contact osteogenesis and bone formation directly on the implant surface only on the modified zirconia implants and the titanium implants, whereas on the machined zirconia surface mainly ingrowth from the surroundings was observed after 6 weeks. The authors concluded that surface-modified zirconia implants showed a resistance to torque forces similar to that of titanium implants and a fourfold to fivefold increase versus machined zirconia implants in the chosen experimental design.

Animal Studies of Loaded Implants

Three studies investigated outcomes with loaded Y-TZP dental implants in animals. The first was done by Akagawa et al in 1993[57] and involved the osseointegration of loaded and unloaded Y-TZP implants in a beagle dog model. A total of 12 implants (Goei Industry) were placed in a 1-stage procedure. The length of the implants was approximately 16 mm with a threaded portion of 9

Table 2 Animal Studies of Loaded Y-TZP Implants

Study	Implant design	Surface treatment	Surgical protocol	Hygiene regime	Loading period	Bone-implant contact
Agakawa et al (1993)[57] (4 dogs, 12 implants)						
Y-TZP experimental; no control	Screw type, diameter 4 mm, length ~16 mm (threaded part 9 mm)	Machined, barrel-polished, ultrasonically cleaned, and autoclaved	Placed 3 mo after extraction; loaded after 1 wk	Brushing 5 days/wk	Unloaded (6 implants) 3 mo (6 implants)	82% 70%
Agakawa et al (1998)[58] (7 monkeys, 28 implants)						
Y-TZP experimental; no control	Screw type, diameter 4 mm, length ~14 mm (threaded part 9 mm)	Machined, barrel-polished, ultrasonically cleaned, and autoclaved	Placed 3 mo after extraction; loaded after 3 mo	Brushing 5 days/wk	12 mo (16 implants): Single implants (4) Connected implants (8) Tooth-connected implants (4) 24 mo (12 implants): Single implants (3) Connected implants (6) Tooth-connected implants (3)	 54%–71%* 58%–77%* 70%–75%* 66%–81%* 66%–77%* 66%–82%*
Kohal et al (2004)[59] (6 monkeys, 24 implants, split-mouth design)						
Y-TZP experimental	Custom made (ReImplant), diameter 4 mm, length 13/15 mm (threaded part ~9/11 mm)	Machined, sandblasted (50-µm Al_2O_3, 3 bar), ultrasonically cleaned,and autoclaved	Placed 5 mo after extraction; abutment connection 6 mo later; abutments kept unloaded for 3 mo	Brushing 6 days/wk with 0.2% chlorhexidine + interdental brushes	5 mo (12 implants)	68%
Control titanium	Same design as Y-TZP	Same treatment; additionally acid etched (H_2O_2/HF) after sandblasting	Same protocol	Same regime	5 mo (12 implants)	73%

*Authors differentiated between buccolingual and mesiodistal sections.

mm and a diameter of 4 mm. The surface of the machined implants was barrel-polished and ultrasonically cleaned with ion exchange water. Three months after extraction, 3 implants were placed in the mandible of each dog. In 2 dogs (the unloaded group) the implants were freestanding with no planned occlusal loading, and the animals were provided with soft food. The 2 dogs in the loaded group received a metal superstructure 1 week after implant placement that splinted the 3 implants and incorporated 1 central occlusal contact on each globular formed crown. These animals received hard-pellet food. Clinical examinations (Plaque Index, Gingival Index, crevicular fluid volume, and probing depth) were performed monthly for 3 months; the animals were then sacrificed and the bone-implant interface was evaluated histomorphologically. No significant differences were found between loaded and unloaded implants for the clinical parameters as well as for the mean bone-implant contact (81.9% ± 11.9% for the unloaded implants, 69.8% ± 14.2% for the loaded implants) (Table 2). However, the authors observed increased marginal bone loss with exposed threads in the loaded group without further quantifying these findings.

In a follow-up study, Akagawa et al[58] used a primate model to investigate the osseointegration of the same implant design under different loading conditions after 12 or 24 months. A total of 32 implants were placed in the mandibles of 8 monkeys in a 1-stage procedure. Three months after implant placement, 3 different types of superstructures were provided in each animal to obtain a different concept of loading support: single implant, 2 implants that were connected, and 1 implant and 1 tooth that were connected. A metal superstructure was cemented directly to the head portion of the implant and provided a central occlusal contact. One animal was excluded from the study following the loss of 1 implant after 2 months. With regard to clinical parameters, no significant differences were found between the different loading groups, the 2 measuring points, or in comparison to the natural teeth. Marginal bone loss was relatively high (1.6 to 2.3 mm at 12 months and 1.7 to 2.1 mm at 24 months). The mean bone-implant contact ranged from 54% to 82% (Table 2). The authors concluded that the Y-TZP implants achieved long-term, stable osseointegration with different concepts of loading support.

Kohal et al[59] investigated osseointegration and peri-implant soft tissue dimensions of loaded zirconia and titanium implants in a primate model in a split-mouth design. Twelve titanium and 12 Y-PSZ implants were custom-made from Y-TZP ceramic blanks using the ReImplant System. The implants were air abraded with Al_2O_3, and the titanium implants were additionally acid etched. The roughened surface ended approximately 3 mm below the implant shoulder for both groups. Five months after extraction of the 4 maxillary incisors, 2 zirconia implants and 2 titanium implants were placed transmucosally, so that the transition line between the rough and smooth surfaces was even with the alveolar crest. After 6 months, titanium abutments were luted on the transmucosal titanium implant and zirconia abutments were luted on the transmucosal zirconia implants. Three months later, single metal crowns were luted to the abutments, and after 5 months in function, the implants were harvested, along with the surrounding hard and soft tissues.

All implants were clinically stable during the experimental time period. No significant differences were found in the mean height of the soft peri-implant cuff (titanium 5.2 ± 1.0 mm, zirconia 4.5 ± 0.6 mm) or for mean bone-implant contact (titanium 72.9% ± 14%, zirconia 67.4% ± 17%; Table 2). No fractures were observed. The authors concluded that, within the limitations of the study, the Y-TZP implants osseointegrated to the same extent as the control implants and showed the same peri-implant soft tissue dimensions.

Discussion

Osseointegration of Y-TZP Dental Implants

In the animal studies reviewed for this paper, osseointegration was evaluated at 4 weeks to 24 months after insertion in different animal models and sites and under different loading conditions. The mean bone-implant contact ratio was above 60% in almost all experimental groups (Tables 1 and 2), indicating successful osseointegration.[60] In those investigations that used titanium implants as a control, zirconia implants were comparable to[54,56,59] or even better than titanium implants.[51] While Kohal et al[59] did not report a higher rate of marginal bone loss for loaded Y-TZP implants, Agakawa et al[57] found apparent loss of crestal bone with exposure of threads in the group of early loaded Y-TZP implants, an observation that was confirmed in their second study (marginal bone loss of 1.6 to 2.3 mm), in which the implants were loaded after 3 months.[58]

The integration process for the bioinert zirconia implants was described mainly as an ingrowth of bone from the surroundings. In the initial healing phase, Scarano et al[55] found direct bone formation on the implant surface, whereas Sennerby et al[56] found direct bone formation only on implants with a modified surface. Davies[61] emphasized the importance of implant surface design and microtopography to achieve what he called “de novo bone formation” on the implant surface itself, in addition to the ingrowth of bone from adjacent bone surfaces.

Roughened surfaces have been shown to support osteoconduction leading to bone formation on the implant surface. In their comprehensive review of dental implant surfaces, Albrektsson and Wennerberg[62,63] reported that moderately roughened titanium surfaces (R_a ~1.5 µm) showed stronger bone response than smoother (machined) surfaces (R_a between 0.5 and 1.0 µm), which may provide some clinical advantages.[62] Furthermore, Sennerby et al[56] found that Y-TZP implants with a moderately roughened surface showed a fourfold to fivefold increase in resistance to torque forces compared with machined Y-TZP implants after 6 weeks of healing. Unfortunately, detailed information on surface microtopography was given in only 1 of the 7 included studies.[56] According to Albrektsson and Wennerberg,[63] it is not considered correct to present comparative data with machined surfaces without further defining surface roughness, for example, as machined surfaces may be smooth like an abutment (S_a = 0.1 to 0.2 µm) or even moderately roughened ($S_a >$ 1.0 µm), which greatly affects bone response to titanium implants. It can be expected that surface microtopography will also be an important factor for the osseointegration of zirconia implants, but few data are available and are based primarily on cell culture tests. Bächle et al[64] found good cell attachment and proliferation of osteoblastlike cells on Y-TZP disks of differently treated surfaces (mean R_a 0.15 to 0.92 µm) comparable to those of a sandblasted/acid-etched titanium surface (mean R_a 1.2 µm). Hao et al[65] investigated the use of laser modification of Y-TZP surfaces for improved osteoblast cell adhesion using a human fetal osteoblast cell line. The laser treatment resulted in smoother surfaces (R_a ~0.2 µm) compared with untreated specimens (R_a ~0.35 µm); surface roughness decreased as the power density of the laser treatment increased. Whereas few osteoblast cells covered less than 10% of the untreated surface, highly dense osteoblast cells covered 70% to 90% of the surface area treated with a carbon dioxide laser. Higher wettability was found on the laser-treated surfaces, caused by the enhancement of the surface energy, particularly the polar component. The authors concluded that the change in wettability characteristics could be the main mechanism governing osteoblast cell adhesion on Y-TZP.

In addition to physical properties, the chemistry of the implant surface can influence the process of early bone formation, as has been demonstrated by the acceler-

ated bone healing around calcium phosphate–based implant materials.[66,67] To improve the osseointegration process, Aldini et al coated Y-TZP implants with a bioactive glass and found faster bone healing[68] and a better osseointegration rate in osteopenic bone.[69]

Clinical Success and Prosthetic Considerations

One clinical study was identified by the electronic literature search[53] and another was found in the secondary literature search.[52] Neither study was included in this analysis because they did not reach evidence level III.[50] Blaschke and Volz[53] reported on 66 implants (Z-Lock3, VOLZIRKON1, and VOLZIRKON2; Z-Systems) that had been inserted between 2000 and 2003 in 34 patients and received zirconia ceramic superstructures 4 months (mandible) or 6 months (maxilla) later. Although the study was said to describe the results of a 5-year implant study in humans, implant success was reported for only 1 to 2 years following insertion; 1 implant fractured as a result of external trauma. No further information on inclusion/exclusion criteria, patient dropout, implant locations, prosthetic reconstructions, and success criteria was given. Conclusions such as "These implants also represent a significant improvement over titanium fixtures" were not based on presented results.

Mellinghoff[52] reported on the clinical results of 189 Z-Lock3 Y-TZP implants (Z-Systems) inserted between August 2003 and December 2005 in 71 patients. The mean observation period was 8.2 months. Only 53 implants (75%) had received a definitive prosthetic reconstruction (zirconia-based crown or fixed partial denture) at the time of the last recall visit. After 1 year, the survival rate was 93%, with 4 implants lost. Because the implants were inserted in the private clinic of the developer and distributor of the implant system and because no information was given on inclusion/exclusion criteria, patient dropouts, implant locations, and prosthetic reconstructions, the study was not included in this analysis.

Whereas at least some limited data are available for Z-Lock Y-TZP implants (Z-Systems), no clinical studies were found for the implant systems of the 4 other manufacturers. With regard to the introduction of new implant surfaces, Albrektsson and Wennerberg[63] concluded that often commercial companies have developed new implant surfaces and introduced them to the market without any prelaunch clinical investigations. In addition, they stated that there is a strong focus on clinical reporting only after the commencement of sales of implants with these surfaces. This view was shared by Walton,[70] who expressed concern that, especially in implant dentistry, an increasing number of new products and techniques have become commercially available without sufficient data on clinical outcomes. It seems that this development is reflected by the introduction of zirconia ceramic dental implants.

Possible prosthetic problems and complications have not been addressed in the available studies. With exception of the SIGMA System (Incermed), only 1-piece Y-TZP implants with a transmucosal healing protocol are available. To establish an excellent esthetic result, especially in the anterior region, these implants must be placed at a perfect angulation and apico-coronal position. Therefore, the use of Y-TZP implants in the esthetically demanding region—where they could potentially have the most benefit—is limited, especially as no clinical data were found for predictable bone augmentation procedures in combination with 1-piece Y-TZP implants.

A possible esthetic advantage of 1-piece zirconia implants, also promoted by some of the manufacturers, is that the location of the margin of the prosthetic restoration can be defined by the clinician by intraoral preparation with diamond instruments, analogous to the preparation of a natural tooth. However, it has been demonstrated that grinding Y-TZP ceramic can lead to increased monoclinic phase transformation and can introduce microcracks that will negatively influence the physical properties of the material.[71–73] This can be expected especially for uncontrolled intraoral grinding of Y-TZP implants, a concern that caused one of the manufacturers (Ziterion) to recommend that intraoral grinding of Y-TZP implants should be strictly avoided. This manufacturer therefore developed a specific implant platform that would enable prosthetic rehabilitation without grinding procedures in most cases. The information on 2-part Y-TZP implants is limited to 1 in vitro study in which the implants restored with 2 different all-ceramic crowns did not sufficiently withstand static and cyclic loading and were thus not recommended for clinical use.[74] It should also be considered that the problem of low temperature degradation of Y-TZP ceramic is still under investigation. A possible solution to overcome the "aging problem" might be the use of zirconia-alumina composites,[39] which are currently being investigated in orthopedic surgery[75] as well as in dentistry.[43]

Conclusions

On the basis of the available data, osseointegration of Y-TZP implants might be comparable to that of titanium implants. Modifications of surfaces and microstructures have the potential to improve initial bone healing and resistance to removal torque, but existing data are few and do not involve commercially available implants.

Published clinical data are restricted to case studies and case series in humans and mainly involve only 1 implant system. Available in vitro data indicate that Y-TZP implants restored with all-ceramic restorations might not sufficiently withstand static and cyclic loading to ensure long-term clinical success. Intraoral preparation of a 1-piece Y-TZP implant is likely to have a negative effect on their long-term stability; the clinical relevance of this issue remains unclear.

Y-TZP implants are prone to low temperature degradation, but the impact of this characteristic on their long-term clinical behavior remains under investigation. Likewise, problems noted with the aging of orthopedic Y-TZP implants in a moist environment may translate to dental Y-TZP implants. To minimize potential hazards, the fabrication process of Y-TZP must be controlled very carefully by the manufacturer.

Y-TZP implants may have the potential to become an alternative to titanium implants but cannot currently be recommended for routine clinical use, as no long-term clinical data are available. To properly evaluate their clinical performance, well-planned, controlled clinical trials with a follow-up of 5 years or more must be performed.

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