Review Article

A systematic review of zirconia as an implant material

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ABSTRACT

The purpose of this systematic review was to assess the published data concerning zirconia dental implants from various aspects.
To identify relevant literature an electronic search was performed of PubMed. Titles and abstracts were screened and articles that fulfilled the inclusion criteria were selected for a full-text reading. Articles were divided into four groups: 1) studies evaluating the mechanical properties of zirconia implants, 2) studies on osseointegration of zirconia, 3) studies on peri-implant tissue response to zirconia implant, and 4) studies on plaque accumulation with zirconia.
Review of the selected articles showed that zirconia implants are reliable for placement in the jaw bone. Furthermore, zirconia implants present a material surface that is compatible with the peri-implant tissue and relatively less attractive to plaque.
Based on the reviewed literature, it appears that zirconia has the potential to become the dental implant material of choice, especially for aesthetic restorations; however, some issues need to be studied further.

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In recent years the treatment options and modalities for achieving optimal functional and aesthetic outcomes with implant restorations have clearly changed.[1] The material of choice for manufacturing dental implants has for long been commercially pure titanium because of its excellent biocompatibilty and mechanical properties.[2,3] However, the gray color of titanium can give rise to aesthetic problems.[3,4] In some situations, there may be a paucity of soft tissue height above the implant level at the time of definitive restoration or, alternatively, this can occur following marginal bone loss and soft tissue recession; in such situations there is an unaesthetic display of the metal components.[5]

Therefore, implant research has focused on discovering tooth-colored implant material that improves the aesthetic appearance of dental implants and, at the same time, is highly biocompatible and able to withstand the forces present in the oral cavity. One ceramic material that has been used for dental implants is aluminium oxide (Al_2O_3).[6–9] It osseointegrated well but was withdrawn from the market because of its poor survival rate.[9–12]

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Zirconia-based ceramics are the latest exceptionally high-strength materials to be introduced into dentistry.[13–15] The strength and toughness of zirconia can be accounted for by its toughening mechanisms, such as crack deflection, zone shielding, contact shielding, and crack bridging.[15] Prevention of crack propagation[16] is of critical importance in high-fatigue situations, such as those encountered in mastication and parafunction.[5] This combination of favorable mechanical properties makes zirconia a unique and stable material for use in high-load situations.[5,17–20]

Zirconia exists in three major phases.[21] At room temperature and atmospheric pressure, the thermodynamic phase of pure zirconia is the monoclinic phase,[21,22] which changes to the intermediate tetragonal phase at higher temperatures. The metastable tetragonal phase easily transforms to the monoclinic phase, which forms the basis for the toughening mechanism of the ceramic material.[23–26]

The osseointegration of zirconia as well as possible clinical outcomes have been demonstrated in various studies. In studies that used titanium implants as a control, yttria-stabilized tetragonal zirconia implants were comparable[3,27–29] to, or even better than, titanium implants.

[30] Zirconia, like titanium, is a biocompatible material and promotes the health of the surrounding soft tissues.[31–35] Zirconia is radiopaque and clearly visible on radiographs. Its ivory color is similar to the color of natural teeth.[36,37] This is especially critical in the aesthetic zone[38–40] and especially with high lip line smiles as it allows for light transmission[39] at the critical interface between marginal gingival tissue and prosthetic components. [1] Furthermore, with the development of dental CAD/CAM systems,[41,42] this high-strength ceramic is becoming the first choice in treating aesthetic implant cases.[1] Besides these favorable properties, zirconia is proposed to accumulate dental plaque to a lesser extent than titanium.[31,41] Further, in a short-term clinical study, it was observed that the biologic, aesthetic, and mechanical properties of zirconia were favorable, and the material could be used in various prosthetic indications on teeth or in implants.[41]

Accumulation of titanium particles has been reported in tissues close to implant surfaces,[43] local lymph nodes,[44] and elsewhere[45,46] in the body. On the other hand, 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.[47–50]

Despite the fact that ceramics have been in use in implant dentistry for many years, only a few systematic reviews of zirconia as an implant material have been published. The purpose of this paper was to assess its potential to become the material of choice for dental implants.

MATERIALS AND METHODS

A literature search was performed of the PubMed database using the following key words: 'zirconia,' 'zirconia implant,' 'zirconia and biocompatibility,' 'zirconia and osseointegration,' and 'zirconia and plaque.' The searches were limited to articles in English and those with an associated abstract. Studies on materials coated with zirconium compounds were excluded.

Literature was reviewed under the following groups:

- *In vitro* studies on the mechanical properties of zirconia implants
- *In vivo* and *in vitro* studies on osseointegration of zirconia implants
- *In vivo* studies on peri-implant/soft tissue response around zirconia implants
- *In vivo* studies on plaque accumulation around zirconia implants

MECHANICAL PROPERTIES

Biaxial flexural strength

Among the studies reviewed, there were three studies[17,51] that assessed the biaxial flexural strength (piston-on-three-ball) of zirconia ceramics. The results achieved by Chai[15] *et al.* [Table 1] were the same as that by Yilmaz.[17] Yilmaz *et al.* observed that the strength of zirconia was higher than that of alumina. Qeblawi[51] subjected zirconia bars to various mechanical treatments [Table 1] and observed a higher flexural strength with airborne particle–abraded zirconia and hand-ground zirconia.

Uniaxial flexural strength

Chai[15] *et al.* compared various ceramic materials and found that yttrium-stabilized zirconia had the highest uniaxial flexural strength of 899 ± 109 MPa.

Fracture toughness

Yilmaz *et al.*[17] studied fracture toughness of different materials by measuring indentation strength and indentation fracture and concluded that the highest fracture toughness values (MPa) were obtained with the zirconia-based ceramic materials.

Shear bond strength

Qeblawi[51] *et al.* subjected the mechanically-treated zirconia specimens (airborne particle–abraded, silicoated, and hand-ground) to three chemical treatments. The highest shear bond strength values were achieved for the silicoated + silanated group and the least by the airborne particle–abraded + zirconia primer group. In the *In vivo* study by Isabella[40] *et al.* in rabbits, no statistically significant difference was observed between chemically-modified implants and topographically-modified zirconia implant.

Stress distribution

Kohal[52] *et al.* did a three-dimensional finite element analysis to analyze stress distribution patterns in implants (re-implant system) made of commercially pure titanium and yttrium-partially stabilized zirconia implants. It was found that yttrium-partially stabilized zirconia implants had very similar stress distribution to commercially pure titanium implants.

Osseointegration

Zirconia-based implants were introduced into dental implantology as an alternative to titanium implants. A number of studies have been done to compare the osseointegration of zirconia implants with that of titanium implants. Most of the studies[30,39,53] have revealed no significant difference between the osseointegration of zirconia implants and that of titanium implants. Depprich *et al.*[54] found similar attachment of both implants to bone, with similar features ultrastructurally. An increased proliferation of osteoblasts was found around zirconia implants as compared to titanium implants, though the attachment and adhesion strength of primary cells was more with titanium. Mosgau *et al.*[55] and Dubruille *et al.*[56] reported higher bone-to-implant contact (BIC) with zirconia than with titanium. Peri-implant bone volume density was

Table 1: Mechanical properties of zirconia

Authors	Materials used	Specimens and parameters	Results
Chai *et al.*[15]	YZ CUBES (YZ Zirconia) (Vita Zahnfabrik), and Cercon (Dentsply). IPS Empress 2 (Ivoclar Vivadent as control In-Ceram Zirconia (IZ) In-Ceram 2000	10 bar-shaped (21 × 5 × 2 mm) 10 disk-shaped (16-mm diameter, 1.2-mm thickness) Uniaxial flexural strength (UFS), biaxial flexural strength (BFS) tested.	For UFS, YZ Zirconia (899 ± 109 MPa) > Cercon (458 ± 95 MPa) >IZ (409 ± 60 MPa) > Empress 2 (252 ± 36 MPa). For BFS, YZ Zirconia (1107 ± 116 MPa) > Cercon (927 ± 146 MPa) > IZ (523 ± 51 MPa) > Empress 2 (359 ± 43 MPa)
Yilmaz *et al.*[17]	6 ceramic core materials [Finesse (F), Cergo (C), IPS Empress (E), In-Ceram Alumina (ICA), In-Ceram Zirconia (ICZ), Cercon Zirconia(CZ)] (15 × 1.2 ± 0.2 mm)	Biaxial flexural strength, Weibull modulus, Indentation fracture toughness	Biaxial flexural strength / Weibull modulus: F: 88.04 (31.61) / 3.17 C: 94.97 (13.62) / 7.94 E: 101.18 (13.49) / 10.13 ICA: 341.80 (61.13) / 6.96 ICZ: 541.80 (61.10) / 10.17 CZ: 1140.89 (121.33) / 13.26 Indentation fracture toughness: Cercon zirconia: 6.27 MPa (0.05) InCeram zirconia: 5.58 MPa (0.18) InCeram alumina: 4.78 MPa (0.18)
Qeblawi *et al.*[51]	Zirconia bars (4 × 5 × 40 mm), zirconia rods (2.5 × 3 mm)	Mechanical treatments for flexural strength (Zirconia bars): (1) control, (2) airborne-particle abrasion, (3) silicoating, and (4) wet hand-grinding. Shear bond strength: (zirconia rods) : above mechanical treatments : chemical treatments: (1) control (no treatment), (2) acid etching + silanation (3) silanation only (4) zirconia primer	Mean flexural strength (SD): 1) Control: 571.7 MPa (79.2): 2) APA: 798.8.3 MPa (138.2) 3) Silicoated: 594.3 MPa (100.5) 4) Hand-ground: 1727.7 MPa (112.7) Shear bond strength: a) No treatment: APA: 15.7 MPa (4.5) b) Acidetch + silanation: hand-ground: 22.2 MPa (4.7) c) Silanated: silicoated: 30.9 MPa (4.6) d) Zirconia primer: handground: 25.5 MPa (2.7)

superior with submerged zirconia implants as compared to titanium implants according to Gahlert *et al.*[53] [Table 2]

Peri-implant tissue compatibility

Two studies evaluated the periodontal parameters with zirconia implants *vs* that with titanium implants. Bleeding on probing remained around 50% for zirconia throughout the study period, while in titanium it was initially 75% but later reduced to 50%. The mean probing depth declined more in zirconia implant as compared to titanium as per Brakel *et al.*[57] Tete *et al.*[58] observed comparable collagen orientation to both zirconia and titanium implants.

Further, lower values of distance from peri-implant mucosa to the apical termination of the barrier epithelium were obtained for zirconia implants according to Wellander *et al.*[59]

Spectrophotometer analysis were also done by two groups of authors[37,59] and both found much lesser mucosa color changes with zirconia implants than with titanium implants [Table 3].

Plaque/bacterial accumulation

We found five studies that assessed the bacterial accumulation around zirconia implants. Brakel *et al.*[57] found more bacterial accumulation around titanium implants than around zirconia implants. Wellender *et al.*[37] found the least number of leukocytes residing around zirconia implants. Rimondini *et al.*[32] compared bacterial adhesion to as-fired and rectified YTZP and titanium using both *in vitro* and *in vivo* studies. *Streptococcus mutans* was found the least with rectified YTZP, comparable to titanium, and maximum with as-fired. *Streptococcus sanguis* showed much less adhesion to both zirconia than to titanium. The study by Rimondini *et al.*[32] also showed significantly lesser cocci and rods in relation to zirconia than titanium. Wellander *et al.*[37] found lesser leukocytes around zirconia implants than around titanium [Table 4].

DISCUSSION

Systematic reviews are useful for evaluating potential materials that may be used for various applications in dentistry. Very few materials have been advocated for use as

Table 2: Osseointegration of zirconia (*In vivo* studies)

Authors	Materials used	Study design/parameters	Results				
Hoffmann[29] (white male rabbits)	Commercially available zirconia implants with roughened surface; titanium implants with sandblasted, acid-etched surface	Bone–implant contact at 2 weeks and 4 weeks		2 weeks	4 weeks		
			Zr	55.4%, 54.8%	62.2%, 80.7%		
			Tit	42.8%, 52.5%	68%, and 91.7%		
Stadlinger *et al.*[30] (minipig mandible)	14 One-piece zirconia implants 7 Titanium implants	Alternately submerged and nonsubmerged zirconia implants (SZr, N-SZr) Submerged titanium implants (STi) bone–implant contact (BIC) and relative peri-implant bone-volume density (rBVD) evaluated		BIC	rBVD		
			SZr	53%	80%		
			STi:	53%.	74%		
			N-SZr:	48%.	63%		
Gahlert *et al.*[53] (15 adult pigs, 30 implants)	Experimental: Threaded zirconia implants (+ acid etching) Control: (Ti-SLA) Titanium implants (sandblasting and acid etching)	Bone-implant contact (BIC) and bone-volume density (rBVD) at 4, 8, and 12 weeks	rBVD:	4 weeks	8 weeks	12 weeks	
			Zr	42.3%	52.6%	54.6%	
			Ti-SLA	29%	44.1%	51.6%	
			BTC:				
			Zr:	27.1%–51.1%			
			Ti:	23.5%–58.5%			
Schultze-Mosgau *et al.*[55]	Y-PSZ cone (Friadent), (1.4 mm × 7 mm) Titanium cone (Straumann), (1.4 mm × 6.5 mm)	Bone implant Contact (BIC), Bone–fibrous connective tissue contact (BFCC)		BIC:BFCC ratio			
			Y-TZP:	1.47 ± 1.12			
			Titanium:	0.97 ± 1.10			
Dubruille *et al.*[56]	Y-TZP (6 implants) Al_2O_3 (6 implants) titanium grade I (6 implants)	Bone–implant contact		Zirconia – 65% Al_2o_3 – 68% Titanium – 54%			
Sennerby *et al.*[63] (12 rabbits, 96 implants)	Y-TZP (24 implants): screw type (Zr) (3.75 mm × 9 mm), surface roughened with pore former A (pfA), surface roughened with pore former B (pfB); Control: screw type titanium (24 implants) (3.75 mm × 7.5 mm)	Bone-implant contact		BIC		RTV	
				Femur	Tibia	Femur	Tibia
			Zr	46%	36%	20 Ncm	12 Ncm
			pfA	60%	56%	98 Ncm	47 Ncm
			pfB	70%	47%	85 Ncm	58 Ncm
			Ti	68%	47%	74 Ncm	42 Ncm

Table 3: Peri-implant tissue compatibility with zirconia implants

Authors	Materials used	Parameters tested	Results				
Brakel *et al.*[57]	Grade 4 Ti screw implants ZrO_2 implants	Probing pocket depth (PPD), recession (REC), bleeding on probing (BOP)		2 weeks		3 months	
				Zr	Ti	Zr	Ti
			PPD:	3.0 ± 1.1	2.9 ± 1.8	1.7 ± 0.7	2.2 ± 0.8
			REC:	2.7 ± 0.6	1.9 ± 1.2	2.1 ± 1.2	2.6 ± 0.1
			BOP:	50%	75%	52.6%	47.4%
Tete *et al.*[58] (30 implants, crestal bone of adult pigs)	Dental implants: 10 with machined titanium neck (Oct-in) 20 with machined zirconia neck (z1)	Collagen fiber orientation; Histologic analysis performed at epithelium–connective tissue junction.		Collagen fibers	G.I.	Probing depth	
			Z1:	48%	0-1	2 mm	
			Oct-in:	58%	0-1	2 mm	
Zembic *et al.*[64] (22 patients, 40 implants)	Customized zirconia abutments, customized titanium abutments	Probing pocket depth (PPD), plaque control record (PCR), bleeding on probing (BOP) and difference in color of mucosa (DE) at abutments (test) and analogous contralateral teeth (control).		PPD	PCR	BOP	DE
			Zr	3.2 ± 1	0.1 ± 0.2	0.4 ± 0.4	9.3 ± 3.8
			Ti	3.4 ± 0.5	0.1 ± 0.2	2.0 ± 0.3	6.8 ± 3.8
Wellander *et al.*[37]	4 implants: 2 titanium abutments (Ti), remaining zirconia (ZrO_2) or Au-Pt abutments	Distance from PM, the margin of the peri-implant mucosa to: B, the marginal level of bone to implant contact, aJE, the apical termination of the barrier epithelium, at 2 and 5 months.		2 months		5 months	
				Zr	Ti	Zr	Ti
			PM: -B	3.08 ± 0.39	3.13 ± 0.33	2.82 ± 0.38	2.85 ± 0.37
			PM: -aJE	1.60 ± 0.31	1.80 ± 0.29	1.75 ± 0.27	1.83 ± 0.22

Table 4: Plaque accumulation with zirconia

Authors	Materials used	Parameters tested	Results
Rimondini *et al.*[32]	As-fired and rectified tetragonal zirconia polycrystals stabilized with yttrium (Y-TZP) and commercially pure grade titanium (Ti)	*In vitro* study: previously inoculated plates with bacteria: *S mutans*, *S sanguis*, *A viscosus*, *A naeslundii*, and *P gingivalis*. *In vivo* study: 10 human volunteers, observed with SEM	Values for As-fired YTZP, Rectified YTZP and titanium, respectively *In vitro* samples: *S mutans*. 0.48 ± 0.02, 0.27 ± 0.01, 0.33 ± 0.01 *S sanguis*. 0.09 ± 0.01, 0.13 ± 0.01, 0.18 ± 0.01 *A viscosus*. 0.15 ± 0.01, 0.14 ± 0.01, 0.16 ± 0.01 *A naeslundii*. 0.21 ± 0.01, 0.30 ± 0.01, 0.20 ± 0.01 *P gingivalis*. 0.08 ± 0.02, 0.09 ± 0.00, 0.11 ± 0.01 Cells on substrates *In vivo*: COCCI- 3.7, 5.0, 4.3 Short rods - 0.7, 1.3, 3.3 Long rods - 0.1, 0.0, 0.8 Keratinocytes - 0.1, 1.0, 0.1
Brakel *et al.*[57]	Grade 4 Ti screw implants ZrO_2 implants	Bacterial aggregation	At 2 weeks, bacterial aggregation with Ti>ZrO2: 7 Ti<ZrO2: 10 At 3 months, Ti>ZrO2: 6 Ti<ZrO2: 11

implants. Zirconia, because of its mechanical strength[2,3] and ivory-like color,[36,37] has been used for many applications in aesthetic zones in dentistry. Following reports of its successful osseointegration in orthopedic cases,[27,47] the osseointegration of zirconia has been studied in the jaws of various experimental animals.

Owing to the ceramic's favorable aesthetic properties and acceptable mechanical properties, we wanted to evaluate zirconia as an implant material. To the best of our knowledge, there have been only few reviews published in literature in this regard. In the present systematic review of literature, most of the parameters have been compared with that of titanium, presently the most commonly used implant material.

The biaxial flexural strength of zirconia implant ranges between 900 and 1100 MPa,[17,21] while the Weibull modulus[17] ranges from 10 to 13. Surface treatments such as airborne particle abrasion and hand-grinding have been found to improve the flexural strength[51] of zirconia implant. The uniaxial flexural strength of zirconia has been found to be 409–899 MPa.[15] Along with strength, the fracture toughness is one of the first parameters to evaluate performance of a dental ceramic. For zirconia implants fracture toughness has been found to be 4–6.2 MPa.[17,21] Also the stress distribution for yttrium–partially stabilized zirconia was similar to that of titanium. In some studies, however, zirconia implant groups have shown irreparable implant head fractures at relatively low fracture loads.[60]

Surface topography and mechanical and chemical treatment of zirconia affect the shear bond strength of zirconia implants. Chemical treatments such as silanation of silicoated zirconia and application of zirconia primer on zirconia have been found to increase the shear bond strength significantly.[51]

An endosseous implant is described as osseointegrated when it is immobile in function. Objective measures of stability testing have been described. The Periotest® is a commercially available device that is used for this purpose.[61] A good number of studies confirm the osseointegration of zirconia to be similar to or even better than that of titanium. Despite the better attachment and adhesion strength of osteoblasts on titanium surface, relatively more proliferation of osteoblasts has been found on zirconia surface.[52] According to literature there is no significant difference in the synthesis of bone-specific proteins on the surfaces of either of these two materials. Similar bone-to-implant contact in zirconia and titanium was seen in many studies.[27,30] It has been further observed that surface roughness on zirconia enhances the bone-to-implant contact.[62,63] The peri-implant bone volume density of submerged zirconia has also been found to be higher than that of titanium.[53] However, further clinical studies need to be carried out to confirm the results from *in vivo* animal studies.

Adequate literature is available on the soft tissue compatibility of zirconia implants and favorable peri-implant response. Soft tissue adhesion with the implant material or an early, long-standing, effective barrier[62] will protect the bone more efficiently from the external environment (i.e., oral cavity) and result in decreased marginal bone resorption.[1] Average probing depth with zirconia implants was 0–3 mm and bleeding on probing[57] was comparable to that seen with titanium implants. Also, the two implant materials show similar thickness of fibrous capsule around the implants,[34] and similar orientation of parallel, parallel oblique, and oblique collagen fibers.[57] Lesser gingival recession was seen after placement of zirconia implants.[58] The aesthetic favorability is also confirmed by studies that show that zirconia induces the least color change under thin mucosa.[64]

Another important parameter to be considered in the selection of an implant material is its affinity towards bacteria/plaque. Lesser plaque accumulation has been reported with zirconia implants.[58] Bacteria such as *S sanguis, Porphyromonas gingivalis*, short rods, and cocci have shown lesser adherence to zirconia than to titanium surface.[32] The adhesion of *Streptococcus* to zirconia has also been shown to similar to that to glass ceramics.[65] There seems to be no difference between polished and glazed zirconia as far as adherence of bacteria is concerned.[66]

CONCLUSION

There is sufficient significant data on various parameters to conclude that zirconia is an aesthetic alternative to titanium implants. As for mechanical properties, zirconia possesses sufficient strength and fracture strength to withstand masticatory forces. However, more studies are needed to evaluate the modulus of elasticity and tensile strength of zirconia as an implant material. The aspect of osseointegration has been adequately covered in literature and it can be concluded that zirconia has as good potential as titanium to osseointegrate with bone. The various *in vivo* studies have shown good peri-implant results, enough to suggest good biocompatibility of zirconia implants with surrounding tissues. Any substantial accumulation of bacteria is also not reported with zirconia implants.

Despite the significant amount of literature supporting the use of zirconia as an implant material, there is need for long-term clinical studies on the subject. Presently, the studies pertain to zirconia's use only as a single-piece implant, hence the nonavailability of zirconia as a multiple piece implant is an added limitation. Because of the lack of clinical reports on the long-term success rates with zirconia implants, the authors suggest caution with regard to certain aspects of zirconia implants, such as tensile strength and modulus of elasticity. Nevertheless, the authors support its clinical use in view of its good osseointegration, aesthetics, and biocompatibility.

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