Zirconia in Fixed Implant Prosthodontics

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ABSTRACT

Background: CAD/CAM technology in combination with zirconia ceramic has increasingly gained popularity in implant dentistry.

Purpose: This narrative review presents the current knowledge on zirconia utilized as framework material for implant-borne restorations and implant abutments, laboratory tests and developments, clinical performance, and possible future trends for implant dentistry are addressed.

Material and Methods: A review of available literature from 1990 through 2010 was conducted with search terms zirconia," "implants," "abutment," "crown," and "fixed dental prosthesis" using electronic databases (PubMed) and manual searching.

Results: Latest applications of zirconia in implant dentistry include implant abutments, multiple unit and full-arch frameworks as well as custom-made bars to support fixed and removable prostheses. High biocompatibility, low bacterial surface adhesion as well as favorable chemical properties of zirconia ceramics are reported. Zirconia stabilized with yttrium oxide exhibits high flexural strength and fracture toughness due to a transformation toughening mechanism. Preliminary clinical data confirmed the high stability of zirconia for abutments and as a framework material for implant borne crowns and fixed dental prostheses. Zirconia abutment or framework damage has rarely been encountered. However, veneering porcelain fractures are the most common technical complication in implant-supported zirconia restorations. These porcelain veneer failures have led to concerns regarding differences in coefficient of thermal expansions between core and veneering porcelain and their respective processing techniques.

Conclusion: As presently evidence of clinical long-term data is missing, caution with regard to especially extensive implant-borne zirconia frameworks is recommended.

KEY WORDS: CAD/CAM, prosthetic design, zirconia

INTRODUCTION

Zirconia ceramics have gained a remarkable interest in biomedical sciences, due to the material's favorable physical, mechanical, biological, and chemical properties.[1–5]

In the early 1990s, zirconia was introduced to dentistry and has been made widely available through the computer-aided design/computer-aided manufacturing (CAD/CAM) technology.[1,3] The successful use of zirconia ceramics for the fabrication of tooth-supported restorations has encouraged clinicians to extend its application for implant-supported restorations. First, results from clinical studies confirmed the high reliability of zirconia as abutment as well as framework material for implant-borne crowns and fixed dental prostheses.[6–9] However, the clinical success of zirconia-based implant-supported restorations is limited by veneering porcelain fractures (chipping), exhibiting the most common technical complication.[7–9] In addition, concerns regarding the long-term stability of zirconia have led to controversial discussions regarding the utilization of zirconia as a substitute for alloys in implant dentistry.[10,11] Compendious information about the properties and outcome of zirconia-based implant-supported restorations would provide the clinicians

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with guidelines and recommendations about the application of this restorative material in implant dentistry. The purposes of this narrative review are to address the current knowledge regarding the properties, the manufacturing, and discuss clinical advantages/disadvantages and survivability of zirconia abutments and frameworks for fixed implant-supported restorations.

A review of available data published from 1990 through 2010 was conducted using electronic databases (PubMed) and manual searching. The search terms used, in simple or multiple conjunctions, were "zirconia," "implants," "abutment," "crown," and "fixed dental prosthesis." Review articles and references from different studies were included to identify relevant studies. An additional manual search was conducted through the bibliographies of all relevant studies and review articles. Because of the limited number of relevant studies, at least for the specific treatment modalities for fixed implant-supported zirconia-based restorations, and the heterogeneity in the design of the different studies identified, it was not possible to perform a statistical analysis of the data.

MECHANICAL PROPERTIES OF ZIRCONIA CERAMICS

The material zirconia, characterized by a dense, monocrystalline homogeneity, possesses a low thermal conductivity, low corrosion potential, and good radiopacity.[12] Yttrium oxide partially stabilized tetragonal zirconia polycrystalline (Y-TZP) exhibits high flexural strength values (900–1200 MPa)[13,14] and fracture toughness (9–10 MPa $m^{0.5}$)[13] owing to a phase transformation toughening mechanism. Y-TZP has been used in root canal posts,[15] frameworks for all-ceramic posterior teeth, and implant-supported crowns and fixed dental prostheses (FDPs),[9,16] custom-made bars to support fixed and removable dental prostheses,[17] implant abutments,[18] and dental implants.[19]

CAD/CAM TECHNOLOGY FOR FABRICATION OF ZIRCONIA ABUTMENTS AND FRAMEWORKS FOR CROWNS AND FIXED DENTAL PROSTHESES

The advantage of industrialized blank fabrication, reproducible, and consistent CAM has largely eliminated human performance inconsistencies with significantly improved reliability and cost effectiveness of CAD/CAM-fabricated zirconia ceramic prosthetic restorations.[20] CAD/CAM technology replaced labor intense waxing, casting, and soldering of frameworks accompanied with conventional laboratory procedures. With the escalating costs of precious alloys, all-ceramic restorations are competitive with conventional restorations from a cost perspective, especially with extensive frameworks used in implant dentistry.[21] There are two types of zirconia milling processes available: a) from pre-sintered blocks; and b) from densely sintered blocks.[22] Examples of pre-sintering systems are Cercon (Dentsply Friadent, Mannheim, Germany), LAVA (3 M ESPE, Seefeld, Germany), Procera (Nobel Biocare; Gothenburg, Sweden), Etkon (Straumann, Basel, Switzerland) and Cerec (Sirona, Bensheim, Germany, IPS e.max ZirCAD, Ivoclar Vivadent, Schaan, Liechtenstein, Germany, Vita InCeram YZ Cubes, Vita Zahnfabrik, Bad Säckingen, Germany). Milling form densely sintered blocks involves machining the framework directly to the desired dimension out of fully sintered zirconia blanks, which have been processed by hot isostatic pressing. Example systems are DC Zirkon (DCS Dental AG, Allschwil, Switzerland) and Denzir (Decim AB, Skellefteå, Sweden). However, because of the extreme hardness of fully sintered zirconia, an extended milling period compared with the pre-sintered milling process is necessary. In addition, the introduction of microcracks in the framework during the milling process has been discussed.[12] Today the pre-sintered milling method is preferred by many manufacturers.

CONSIDERATIONS ON ZIRCONIA AS A RESTORATIVE MATERIAL

Low Temperature Degradation (LTD)

A major drawback for zirconia restorations is the material inherent accelerated aging.[23] In a humid environment, spontaneous slow transformation from the tetragonal phase to the more stable monoclinic phase occurs in zirconia grains at relatively low temperatures of 150–400°C. This aging phenomenon is known as LTD. This process initiates at surface grains, and then later progresses toward the bulk material causing a reduction in flexural strength of the material, putting it at risk of spontaneous catastrophic failure.[24,25] This problem mainly involves frameworks or parts of a framework that are not subjected to porcelain veneering and zirconia implant abutments that are exposed to the oral environment. Non-veneered zirconia frameworks should therefore be avoided. During framework design, it is advisable to ensure appropriate space for coating of all zirconia surfaces by a thin porcelain of glass layer.

Because present clinical data is limited to 5-year observation periods, the relationship between aging of zirconia frameworks and long-term clinical performance need to be investigated in further evaluations.[12]

Veneering Ceramic Failure

A variety of reasons for zirconia veneer failure and mainly the mismatch of the coefficients of thermal expansion (CTE), as well as the bond strength between the veneering porcelain and the zirconia substructure, have been discussed.[12] All available zirconia brands exhibited chipping fractures, even when using specifically manufactured veneering porcelains with modified CTE compatible with zirconia ($>11 \times 10^{-6}$/K). All reported clinical fractures were exclusively cohesive failures limited to the veneering ceramic material (Figure 1),[7,9] without delamination of the veneering ceramic or interfacial spreading of the cracks. This type of failure mode indicates a sufficient interfacial bond between the core and the veneer materials, which has also been confirmed by recent in vitro shear bond test results.[26] As the veneering ceramic material (flexural strength ~ 90–120 MPa) is weak, compared with the high-strength core material (900 MPa), the veneering ceramic is prone to fail at low loads during masticatory function. Consequently, it has been concluded that improving its strength could reduce the incidence of veneering porcelain chipping. However, attempts to improve the microstructure and mechanical properties of veneering ceramics with development of glass-ceramic ingots for pressing veneering ceramics onto zirconia frameworks did not result in an increased reliability.[27,28] Cohesive veneer fractures have also been reported in pressed porcelain in clinical trials on zirconia FDPs.[29]

Swain 2009[30] proposed that tempering residual stresses were the basis for the preponderance of chipping of porcelain bonded to zirconia. Three factors which contribute to these residual stresses were

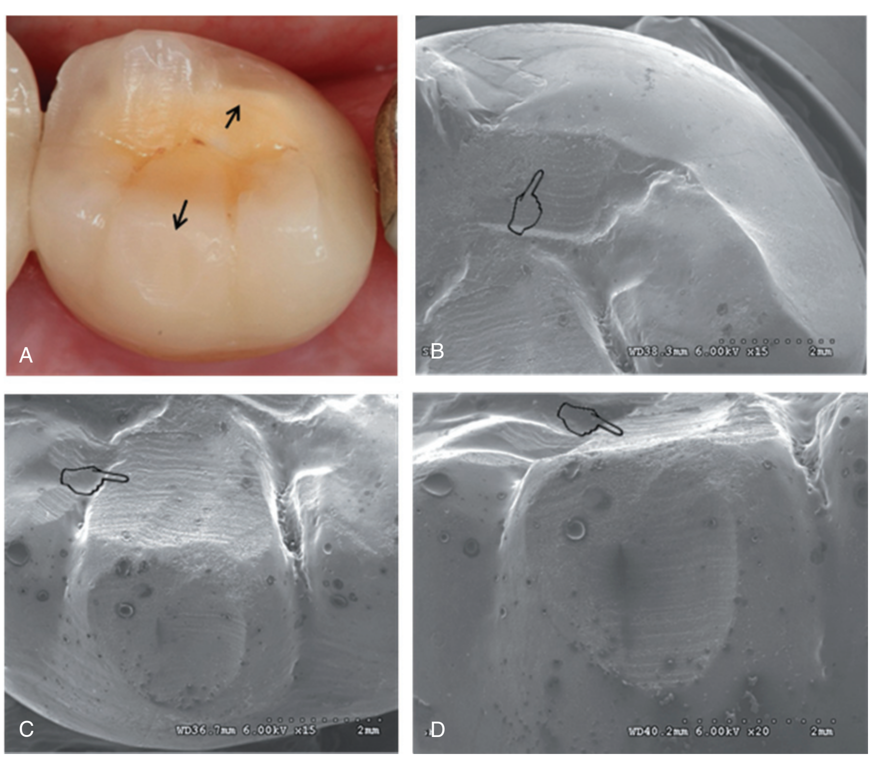

Figure 1 Clinical example and replica evaluation of a cohesive veneering ceramic failure of a zirconia-based implant-supported crown. *A*, Clinical photograph of chip-off fractures (arrows) of a veneered zirconia-based implant crown after 13 months of service. *B*, Scanning electron microscopy (SEM) capture of corresponding mesio-lingual area. Pointer shows the rough surface area, created by occlusal adjustments, supposedly forming the fracture initiation site. *C*, SEM capture of similar fracture pattern in the mesiobuccal area in occlusal view. Occlusal grinding traces are evident (pointer). *D*, SEM capture of the buccal view depicts the connection of the occlusal adjusted area with the adjacent chip-off fracture within the veneering ceramic.

summarized: mismatch of the higher CTE of porcelains bonded to zirconia,[31] thickness of the veneering porcelain, and cooling rate. The cooling rate after the removal of the sintered restoration from the furnace generates significant thermal gradients within the porcelain and is directly related to the low thermal conductivity of zirconia,[32] which is much lower than that of metal alloys and alumina ceramic, showing lower incidences of chipping fractures. Slow cooling of the restoration above the glass transition temperature of the porcelain could prevent the development of high tensile subsurface residual stresses in the porcelain. Reduced cooling rates after final firing or glazing are now recommended by most manufacturers.

Framework Design

Framework design practices of all-ceramic restorations have been based more upon empirical guidelines than upon clinically relevant scientific data. Remarkably, little scientific data on optimal design of zirconia-based restorations have been published.[33] Various framework design proposals with debatable clinical relevance and impact on chipping fracture were described for posterior implant FDP restorations.[34] Based upon finite element analysis data, the shape of the framework and particularly the shape of the pontic connector interface affects the stress distribution, fracture strength, and fracture mode of implant-supported zirconia FDPs.[35]

The lack of a uniform support of the veneering ceramic due to improper framework design has been suggested to be a contributing factor in chipping fractures.[9,21] This aspect is of particular interest in implant dentistry due to prevalent increased inter-abutment as well as inter-arch distance related to extensive bone loss. With the beginning of CAD/CAM technologies in dentistry, excessive veneer layer thickness (>2.5 mm) was created due to uniform layer thickness of the copings for crowns as well as bar-shaped connectors for FDPs. An improved customized zirconia coping design that provides adequate support to the veneering porcelain has been derived from the conventional porcelain fused to metal technique.[33] A dual-scan procedure of the die and full-contour wax pattern has been merged to fabricate the desired framework. Tinschert and colleagues[36] adopted this modified framework design in teeth-supported zirconia FDPs and Nothdurft and colleagues[7] in implant-supported zirconia crowns; however, chipping fractures still occurred. Nevertheless, the impact of framework design modifications on residual stress states needs to be addressed in further research. Because of the low thermal conductivity of zirconia, an evaluation of the existing firing programs for the veneering process of zirconia frameworks may require modifications to avoid underfiring of the veneering ceramic.[37] Until more is known about clinical failure modes and clinical long-term performance parameters, precise recommendations cannot be made with confidence.

CONSIDERATIONS ON FIXED IMPLANT RESTORATION DESIGNS

Treatment options for fixed implant-supported restorations include single crowns or FDPs. The treatment alternatives comprise primary (screw-retained restorations) or secondary splinting (single abutments with a cemented restoration) of the implants (Figure 2). Because of technological advances, it is possible today to fabricate screw-retained, zirconia-based, all-ceramic FDPs. Facilitating retrievability, such FDPs are designed and manufactured in a one-piece zirconia substructure to the implant-fitting surface. The implant-supported framework is milled from a single block of zirconia to either the implant level or the abutment level. Porcelain is then directly fired onto the abutment/zirconia framework, and the abutment crown/FDP complex can be screwed onto the implant (Figure 3). Possible complications of such restorations include chipping of the veneering ceramic due to the discontinuity of porcelain at the central screw access opening.[38] With few case reports available, long-term clinical data about the survival rates of multiple screw-retained zirconia frameworks are currently lacking.[39,40] Despite limited scientific evidence, some manufacturers allow the fabrication of implant-supported, multi-unit, and full-arch restorations with screw-retained zirconia frameworks. On the other hand, cement-retained restorations on individual ceramic abutments enable to compensate for misaligned implants; the potential difficulty in retrieving the restoration represents a disadvantage of such restorations. Reliable evidence-based scientific data favoring one treatment option over another are currently not available.[41] The incorporation of cantilevers into such implant-supported FDPs can be associated with a higher incidence of technical complications related to the suprastructures. In vitro data on zirconia-based cantilever FDP framework designs showed poor fracture

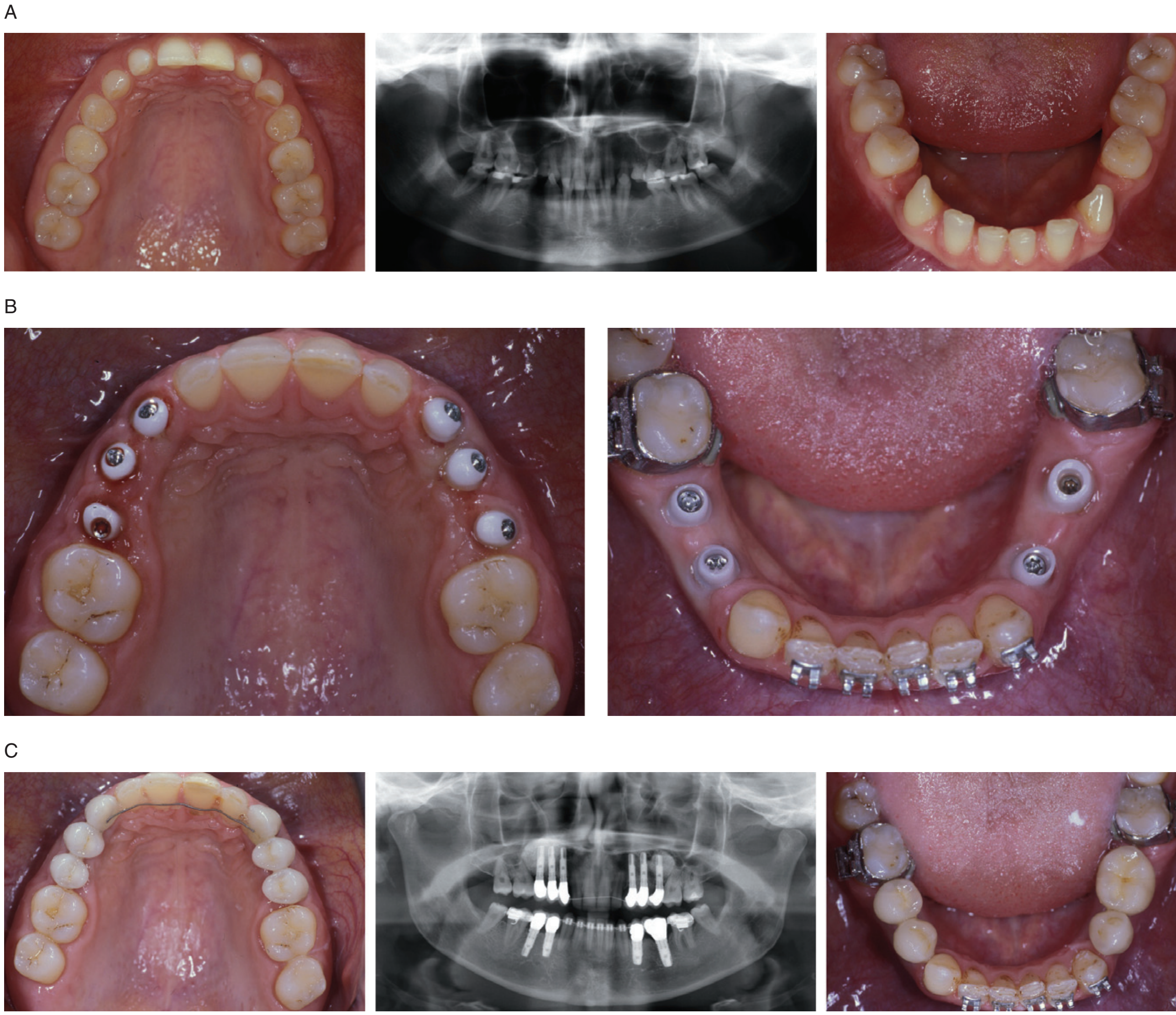

Figure 2 Clinical example of cemented zirconia-based implant-supported single restorations. *A*, Occlusal view and radiograph of the clinical situation. The patient presented with congenitally missing premolars and canines in the maxilla (left) and premolars in the mandible (right). *B*, The deciduous teeth were extracted and implants were placed (Nobel Replace, Nobel Biocare, Göteborg, Sweden). Zirconia abutments (NobelProcera Zirconia, Nobel Biocare, Göteborg, Sweden) were screwed onto the implants in the upper (left) and lower jaws (right). *C*, The patient received zirconia-based single crowns (NobelProcera Zirconia, Nobel Biocare, Göteborg, Sweden) that were cemented on the zirconia abutments in the upper (left) and lower jaws (right). Control radiograph after delivery of final restorations (middle).

resistance.[42] Hence, zirconia-based cantilever FDPs are not recommended as a treatment alternative.

ZIRCONIA ABUTMENTS

Today, the majority of implant manufacturers offer zirconia abutments for aesthetic implant-supported restorations. Abutments are available in prefabricated or customized forms and can be prepared in the dental laboratory either by the technician or by utilizing CAD/CAM techniques. Zirconia abutments are successors to the densely sintered high-purity alumina (Al_2O_3) abutments. Compared with the latter, zirconia abutments are radiopaque and demonstrate significantly higher resistance to fracture property.[43] As an abutment material, the biocompatibility of zirconia toward soft connective and epithelial tissue is essential. To determine the biocompatibility or interactions at the biomaterial–tissue interface, in vitro studies using cell cultures have been carried out.[44] It is well known today that ceramics, including zirconia, are highly biocompatible and are less prone to plaque accumulation than metal substrates.[45–47] On the other hand, it is commonly agreed that ceramic

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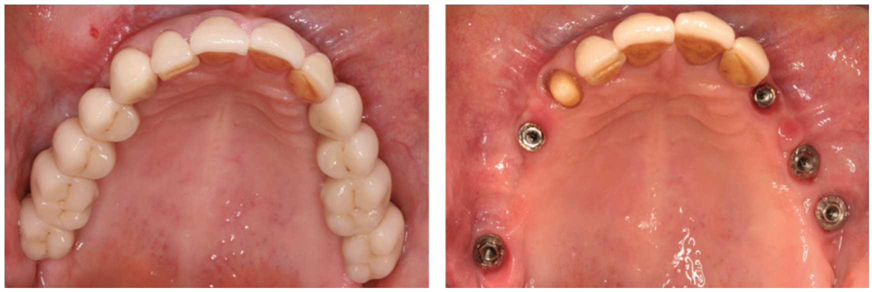

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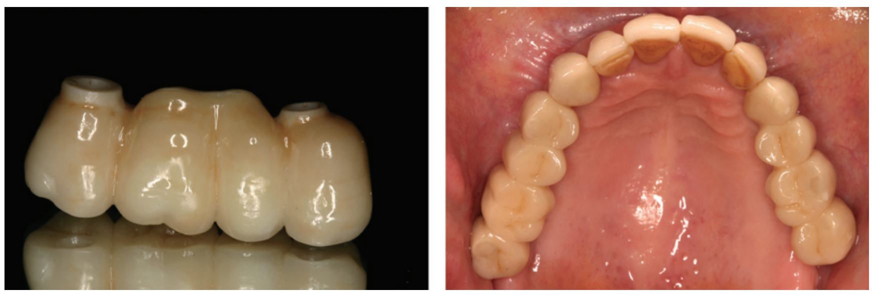

Figure 3 Clinical example of one-piece zirconia fixed dental prostheses (FDPs) fitted directly onto the implant platform. *A*, Occlusal view of the clinical situation. The patient presented with palladium allergy (left), which indicated the removal of the current metal-ceramic implant-supported restorations (right). *B*, Zirconia-based implant-supported FDP (left). The framework was milled out of a zirconia block (Zirkonzahn, Gais, Italy) and veneered with a press-on ceramic (e.max ZirPress, Ivoclar Vivadent, Schaan, Liechtenstein, Germany). Occlusal view of the screw-retained zirconia restorations. Occlusal screw access holes were closed with a composite resin (right).

abutments should show proper resistance against masticatory forces raised during chewing or swallowing. Several studies reported a mean loading force of approximately 206 N and maximum biting forces of up to 290 N in the aesthetic zone.[48,49] In an in vitro study, unprepared titanium-reinforced zirconia and pure alumina abutments were compared for their outcome. After fatigue and static loading, the median fracture loads were 294 N, 239 N, and 324 N for the zirconia, alumina, and titanium abutment groups, respectively.[50] The authors concluded that titanium-reinforced zirconia abutments perform in a similar manner to metal abutments, and can therefore be recommended as an aesthetic alternative for the restoration of single implants in the anterior region. In another in vitro study, different implant-zirconia abutment combinations were tested for their load fatigue performance. Although no significant differences were found between the implant systems, differences were observed between the implant diameters. The authors concluded that rotational load fatigue testing performance of zirconia abutments is dependent on the abutment diameter.[51] A recent systematic review evaluating laboratory studies about the resistance of implant abutments with/without restorations identified nine studies evaluating zirconia abutments.[6] We additionally identified one further study (Table 1).[52] Although no implant-supported FDPs with zirconia abutments were tested, the majority of studies identified used implant-supported single crowns. The resistance-to-fracture values for samples not subjected to fatigue loading and samples subjected to fatigue loading ranged from 131 N to 737 N and from 57 N to 593 N, respectively (Table 1). Because of the heterogeneity in study design and testing methods employed in different studies, it was not possible to carry out a meta-analysis of the data. Observing the identified laboratory studies, it can be noticed that all zirconia abutments tested were not modified in their dimensions. Generally, the clinical application of prefabricated zirconia abutments necessitates grinding procedures and reduction in wall thickness. It should be expected that the resistance of prepared zirconia abutments might be different than that of unprepared ones. Unfortunately, the current literature does not provide information about this issue. Hence, there is a need to explore the effect of grinding procedures on the resistance of zirconia abutments as well as to identify a minimal wall thickness that guarantees long-term stability. The lack of knowledge about the

TABLE 1 Fracture Strength of Zirconia Abutments: Laboratory Studies

Author/Year	Implant System	Abutment	Abutment Material	Restoration	Restorative Material	Fatigue Loading	Mean Fracture Load (N)
Att et al. 2006a[53]	Nobel Replace, Nobel Biocare	Aesthetic zirconia	Zirconia	SC/Maxillary incisor	Procera Alumina	TCML	470
Att et al. 2006b[67]	Nobel Replace, Nobel Biocare	Aesthetic zirconia	Zirconia*	SC/ axillary incisor	Procera Zirconia	TCML	593
Butz et al. 2005[50]	Osseotite 3i	ZiReal	Zirconia with titanium insert	SC/Maxillary incisor	Non-precious metal	TCML	
Gehrke et al. 2006[68]	Xive, Dentsply Friadent	Cercon	Zirconia	Spherical caps/Maxillary incisor		TCML	269
	Xive, Dentsply Friadent	Cercon	Zirconia			No	672
Sailer et al. 2009[69]	Straumann standard	CARES	Zirconia	SC/Maxillary incisor	All-ceramic	No	378
	Brånemark standard	Procera	Zirconia				416
	Replace	Procera	Zirconia				490
	Straumann standard	Zirabut	Zirconia				246
Sundh & Sjoegren 2008[70]	Straumann	Denzir M	Magnesia-zirconia	Ceramic copy	Ceramic	No	430
	Straumann	Denzir	Zircnia				470
Wiskott et al. 2007[71]	Replace Select	Aesthetic Zirconia	Zirconia	—	—	TCML	56
Yildirim et al. 2003[72]	Brånemark standard	Wohlwend	Zirconia	SC/Maxillary incisor	Glass-ceramic	No	738

SC, single crowns; TCML, thermo-cycling and mechanical loading.

outcome of zirconia abutments in restorative systems other than single crowns, as well as the effect of the abutment's design on its resistance implicates the necessity for further evaluation of these parameters under laboratory conditions before clinical application.

In contrast to laboratory studies, less information is available on the clinical outcome of zirconia abutments (Table 2). With observation periods between 6 months and 4 years, the survival rates of zirconia abutments were 100%. Despite encouraging short-term results, there is a need for long-term clinical data about the outcome of zirconia abutments.

OUTCOME OF IMPLANT-SUPPORTED ZIRCONIA-BASED FIXED RESTORATIONS

The fracture strength of implant-supported zirconia-based fixed restorations has been evaluated in a small number of laboratory studies (Table 3). Only seven investigations with various testing protocols and study designs could be identified. For zirconia-based implant-supported single crowns, the resistance-to-fracture values amounted to 593 N.[53] For implant zirconia-based FDPs, the resistance-to-fracture values ranged between 424 N and 1691 N. Initial restoration failure was caused by failure of the veneering ceramic.

Clinical data concerning treatment outcome of zirconia-based implant-borne restorations are still scarce. Apart from case reports, only three short-term clinical studies on zirconia-based, implant-supported crowns and FDPs could be identified (Table 4). Implant-supported, zirconia-based single crown restorations revealed fracture rates within the veneering ceramic ranging from 7.5 to 18.5% after 6 and 15.3 months.[7,8] Even higher veneer failure rates (41 to 53% after 12 and 13 months) were reported with implant-supported, zirconia-based FDPs.[8,9] None of the studies revealed zirconia framework fractures of the implant-supported single crowns or three-unit FDPs.[7–9]

In summary, implant-supported zirconia-based crowns and FDPs exhibited an unacceptable amount of veneer chipping failures. Impaired proprioception and rigidity of osseointegrated implants correlated with higher functional impact forces might further exacerbate porcelain fractures. To our knowledge, no clinical studies have been published on rehabilitation with multi-unit or full-arch, implant-supported zirconia FDPs. As a matter of fact, reliability of implant-

TABLE 2 Clinical Outcome of Zirconia Abutments

Author/Year	Implant System	Abutment	Cement	Study Design/ Restoration/Material	Number of Restorations	Observation Period	Survival Rate Abutments	Survival Rate Restorations	Complications
Nothdruft & Pospiech 2009[7]	Xive, Dentsply Friadent	Zirconia (Cercon, Dentsply Friadent)	Resin modified glass-ionomer	Prospective/Posterior Y-TZP SC	40	6 months	100%	NR	Chipping of veneering ceramic 7.5%
Zembic et al. 2009[73]	Brånemark, Nobel Biocare	Zirconia (Procera, Nobel Biocare)	Resin cement	RCT/glass ceramic, alumina or zirconia SC	18	3 years	100%	100%	—
Canullo 2007[74]	TSA, Implandent	Zirconia abutments with titanium connection	Resin cement	Prospective/zirconia SC	30	3.3 years	100%	100%	—
Glauser et al. 2004[18]	Brånemark, Nobel Biocare	Zirconia, Nobel Biocare	Resin cement	Prospective/ press-ceramic SC	54 abutments/ NR	4 years	100%	NR	—

SC, single crowns; NR, not reported; Y-TZP, yttrium oxide partially stabilized tetragonal zirconia polycrystalline.

supported, zirconia-based restorations with greater extensions must be investigated.

RECOMMENDATIONS FOR CLINICAL PROTOCOLS

A number of fundamental aspects affecting the clinical performance of zirconia as framework material in implant dentistry need to be addressed.[54] Laboratory technicians and clinicians should follow precise sequence steps in manufacturing zirconia-based restorations with the knowledge that zirconia as a framework material is highly susceptible to surface modifications, and improper laboratory and clinical handling techniques.[55]

If any subtractive procedure is performed after final sintering of the zirconia ceramic, for example, sandblasting or grinding of the intaglio surface to increase the roughness for cementation purposes or adjustment of the same surface for better fit, a monoclinic phase will most likely be observed on the treated surface. This monoclinic transformation will, in the first instance, increase the strength of the restoration.[56,57] However, when a crack initiates in that area, there is no transformation toughening mechanism available anymore to oppose crack propagation as the tetragonal phase was already transformed.[58,59] Furthermore, grinding or sandblasting of surfaces with high (or mild/low) pressure ranges is discussed to induce the formation of surface microcracking[60] that could be detrimental to the long-term performance of the restorations and lead to unexpected failures.[61] Moreover, sandblasting has been reported to cause marginal defects and widen the gap between the crown and implant abutment.[62,63] However, sandblasting prior to cementation procedures is presently discussed with conflicting statements in the dental literature. Long-term clinical studies will be the ultimate goal to demonstrate whether treatment of the intaglio surface is of concern clinically.[12,54]

Based on the above-mentioned aspects, post-sintering surface modifications of zirconia framework at the dental laboratory or at the dental clinic should be limited to essential.

Recently published clinical data on the performance of teeth-supported, zirconia-based restorations revealed that chip-off fractures of the veneering ceramics were prevalently associated with roughness of the veneering ceramic because of grinding or occlusal function.[64] Analysis of the crack propagation direction showed that

TABLE 3 Fracture Strength of Implant-Supported Zirconia-Based Crowns and FDPs: Laboratory Studies

Author/Year	Implant System	Abutment	Cementation	Restoration/ Framework Material	Veneering Material	Fatigue Loading	Mean Fracture Load (N)
Att et al. 2006[53]	Replace Select, Nobel Biocare	Y-TZP Abutments (Aesthetic Zirconia, Nobel Biocare)	Resin cement	Anterior SC/Procera Zirconia, Nobel Biocare	VM9, Vita Zahnfabrik	TCML	593
Kokubo et al. 2007[34]	NR, Straumann	NR	Resin cement	Posterior three-unit FDPs/Procera Zirconia, Nobel Biocare three framework/ bar designs	Creation, Geller	No fatigue	Initial crack/final fracture Straight bar: 1292 644 Occlusal curve: 1398 476 Gingival curve: 1040 722
Tsumita et al. 2008[35]	Branemark Mk III, Nobel Biocare	Titanium (Procera, Nobel Biocare)	NR	Posterior 3-unit FDPs/Cercon Base, Degudent three framework/ bar designs	Cercon Ceram S, Degudent	No fatigue	Initial crack/final fracture Regular pontic: 682 916 Occlusal curve: 439 1691 Gingival curve: 945 1516
Nothdurft et al. 2010[7]	Xive S, Dentsply Friadent	Y-TZP (Cercon, Dentsply Friadent) Standard, individualized	Glass-ionomer cement	Posterior three-unit FDPs/Cercon Base, Dentsply Friadent	No Veneer	No fatigue/TCML	Abutment: Stand. Indiv. No fatigue 473 424 TCML 647 556
Bonfante et al. 2009[75]	NR, Nobel Biocare	Abutment Replicas (Replica Snappy Abutment, Nobel Biocare)	Resin Cement	Posterior three-unit FDPs/(LAVA, 3MEspe)	LAVA Ceram, 3MEspe	Accelerated Step-stress fatigue	Prior to fatigue: 693 Load at which 63.2% would fail: 497

SC, single crowns; NR, not reported; TCML, thermo-cycling and mechanical loading; FDPs, fixed dental prostheses; Y-TZP, yttrium oxide partially stabilized tetragonal zirconia polycrystalline.

TABLE 4 Clinical Outcome of Implant-Supported Zirconia-Based Crowns and FDPs

Author/Year	Implant System	Abutment	Cementation	Study Design Restoration/Material	Number of Restorations	Observation Period	Abutment Fracture Incidence	Framework Fracture Incidence	Veneer Fracture Incidence
Nothdurft & Pospiech 2009[7]	Titanium (Xive S, Dentsply Friadent)	Y-TZP Abutments (Cercon, Dentsply Friadent)	Resin – modified glass-ionomer	Prospective/Posterior SC/Cercon, Dentsply Friadent	40 SC	6 months	0%	0%	7.5%
Kohal et al. 2009[8]	Y-TZP one-piece (n.s., Nobel Biocare)	NA	Glass-ionomer cement	Prospective/SC and 3-unit FDPs/Procera Zirconia, Nobel Biocare	65 SC 27 FDPs	15.3 months 13 months	n.a.	0%	18.5% 41%
Larsson et al. 2006[9]	Titanium (Astra Tech Standard, Astra Tech)	Titanium Abutments (Astra Tech ST, Astra Tech)	Zinc phosphate Cement	Prospective/Posterior 2-5-unit FDPs/ Denzir, Decim, Dentaurum	13 FDPs	12 months	0%	0%	53%

SC, single crowns; NA, not applicable; FDPs, fixed dental prostheses; Y-TZP, yttrium oxide partially stabilized tetragonal zirconia polycrystalline.

the chipping failures in almost all FDPs had originated from a roughness of the ceramic at the occlusal region of the cusps.[64] Propagation of surface flaws induced during occlusal adjustments can result in veneer fracture (Figure 1).[9] Therefore, special attention has to be paid to the static and dynamic occlusion of zirconia-based, implant-supported restorations.[7] Occlusal adjustments should only be performed with fine grain diamonds, followed by a thorough polishing sequence.

FUTURE OF ZIRCONIA IN FIXED IMPLANT PROSTHODONTICS

To overcome chipping fractures of veneered zirconia restorations, a novel approach in veneering zirconia copings has been recently described.[65] Sintering a CAD/CAM-milled lithium disilicate veneer cap onto the zirconia coping has significantly increased the mechanical strength of crown restorations and represents a cost-effective way of fabricating all-ceramic restorations. To date, there are no clinical studies that have adopted this method, and further in vitro studies are needed before this type of restoration can be clinically trialed.

The functionally graded glass/zirconia/glass (G/Z/G) structure could be another concept.[66] The coating of the top and bottom of a pre-sintered Y-TZP with a slurry of glassy powder results in an increased damage resistance, translucency, and will also allow etching and silane application for reliable bonding mechanisms. A similar approach with full-anatomic zirconia framework and subsequent surface characterization and glazing has been established with the Zirkonzahn (Zirkonzahn GmbH, Gais, Italy) production line. However, no clinical data is available yet, and concerns regarding antagonistic wear are raised.

Robocasting technology generating three-dimensional, custom-made layered structures will be a promising fabrication method for the future of zirconia in dental application. A variety of structures with changing or graded configuration can be produced by using colloidal pastes, slurries, or inks with different compositions of alumina and zirconia, to determine the specific mechanical characteristics of the final product.

The unclear effect of LTD on long-term behavior as well as the susceptibility to veneer fracture has led clinicians to question zirconia and to search for alternative materials. Monolithic CAD/CAM-fabricated, full-anatomic lithium disilicate glass-ceramic restorations are recently explored with promising results for crown application. In addition, innovative ceramic composite compound materials could combine the aesthetical features of the ceramic with the favorable mechanical properties of the composite component with regard to load bearing capacity.

CONCLUSIONS

Fracture of the veneering ceramics and the susceptibility of zirconia to aging are major concerns for the clinical long-term success of zirconia in fixed implant prosthodontics. Presently, there are very limited clinical data available evaluating the performance of zirconia abutments and implant-supported fixed restorations. Therefore, it cannot be recommended for use in daily private practice.

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