Zirconia in Dentistry: Part 2. Evidence-based Clinical Breakthrough

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Abstract

An ideal all-ceramic restoration that conforms well and demonstrates enhanced biocompatibility, strength, fit, and esthetics has always been desirable in clinical dentistry. However, the inherent brittleness, low flexural strength, and fracture toughness of conventional glass and alumina ceramics have been the main obstacles for extensive use. The recent introduction of zirconia-based ceramics as a restorative dental material has generated considerable interest in the dental community, which has been expressed with extensive industrial, clinical, and research activity. Contemporary zirconia powder technology contributes to the fabrication of new biocompatible all-ceramic restorations with improved physical properties for a wide range of promising clinical applications. Especially with the development of computer-aided design (CAD)/computer-aided manufacturing (CAM) systems, high-strength zirconia frameworks can be viable for the fabrication of full and partial coverage crowns, fixed partial dentures, veneers, posts and/or cores, primary double crowns, implant abutments, and implants. Data from laboratory and clinical studies are promising regarding their performance and survival. However, clinical data are considered insufficient and the identified premature complications should guide future research. In addition, different zirconia-based dental auxiliary components (ie, cutting burs and surgical drills, extra-coronal attachments and orthodontic brackets) can also be technologically feasible. This review aims to present and discuss zirconia manufacturing methods and their potential for successful clinical application in dentistry.
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Introduction

The growing belief that metal-free dentistry will alter the traditional restorative spectrum had always been stymied by the inherent brittle nature of dental ceramics. Therefore, researchers and manufacturers have developed advanced formulas to prevent crack propagation mainly by using yttrium-tetragonal zirconia polycrystals (Y-TZP), commonly known as zirconia.[1-3] The advent of zirconia ceramics, in conjunction with computer technology, has led both dental science and industry to experience their own "dream." The interpretation of this specific "zirconia dream" could be defined as "the general clinical application of a highly biocompatible zirconia ceramic material that is resistant on a long-term basis to all thermal, chemical, and mechanical impacts of the oral environment in a wide range of dental restorations." Over the last decade, the dental community has been a witness to an industrial "big bang" regarding zirconia processing for different applications in dentistry.[4,5] The latter developments were characterized by a global promotion that created great expectations, but on the other hand, the new technology seems to need a certain amount of time to be fully adapted by dentists and dental technicians. The dental profession is aware of the limited clinical data regarding strength resistance under fatigue, bonding effectiveness, color performance, and longevity of the zirconia-based restorations.[6] Nevertheless, dreaming may let us glimpse the future, or even better according to the "expectation fulfillment theory,"[7] it could realistically complete patterns of emotional expectation that encourage research and clinical trials concerning this evolving biomaterial.

Nowadays, zirconia technology has fallen into step with computer-aided design/computer-aided manufacturing (CAD/CAM) systems that promise to transform everyday dentistry.[8] The three-dimensional design of Y-TZP frameworks requires a computer and special software (CAD) provided by the manufacturer. After a scanning procedure of the designed work, data are transferred to a computerized manufacturing unit (CAM) that performs a preset production of the zirconia framework.[9] Zirconia-based frameworks are produced either by milling out from a solid block (subtractive technique),[10] predominantly for Y-TZP ceramics, or by using electrophoretic deposition (additive technique) particularly for cerium-tetragonal polycrystal (Ce-TZP) ceramics.[11] Milling of zirconia blocks can be performed in the partially[12] or fully sintered stage[10] using appropriate cutting diamonds under water coolant if needed. The majority of CAD/CAM systems utilize partially sintered Y-TZP ceramics, where the milling procedure is performed with the use of carbide burs in a dry environment. Throughout the designing stage, the size of a prospective milled, partially sintered framework is analogically enlarged approximately 20% and 25% in comparison with the original dimensions, due to the shrinkage occurring after the final sintering.[13] Moreover, milling of fully sintered or hot isostatically pressed (HIP) zirconia blocks is time-consuming due to the increased hardness of the material, but it does not exhibit any dimensional changes (ie, shrinkage). Processing of partially sintered Y-TZP ceramics at room temperature presents limited surface or in-depth damage (ie, voids, flaws, cracks),[14] in contrast with hard machining of fully sintered (or HIP) that might induce microcracks.[15] Nevertheless, sur-

Table 1 Current CAD/CAM systems for Y-TZP zirconia processing (in alphabetical order).

System	Company	Website
Cad.esthetics®	Cad.esthetics (Skelleftea, SE)	http://www.cadesthetics.com
Cynovad Neo™	Cynovad (Saint-laurent, CD)	http://www.cynovad.com
CentraDent	CentraDent (Haarlem, NL)	http://www.centradent.nl
Ceramill Multi-x	Amann Girrbach (Koblach, AU)	http://www.amanngirrbach.com
Cercon®	DeguDent (Hanau, DE)	http://www.degudent.de
ce.novation®	Inocermic (Hermsdorf, DE)	http://www.cenovation.de
inLab® MC XL	Sirona Dental Systems (Bensheim, DE)	http://www.sirona.com
Cyrtina®	Oratio (Zwaag, NL)	http://www.oratio.nl
DentaCAD	Hint-ELs (Griesheim, DE)	http://www.hintel.de
Diadem	Alkom Digital (Luxembourg, LU)	http://www.alkom-digital.com
Digident®	Digident (Pforzheim, DE)	http://www.digident-gmbh.com
Etkon™	Etkon (Graefelfing, DE)	http://www.etkon.de
Everest	KaVo (Leutkirch, DE)	http://www.kavo-everest.de
GN-1	GC Corporation (Tokyo, JP)	http://www.gcdental.co.jp/english/index.html
infiniDent	Sirona Dental Systems (Bensheim, DE)	http://www.infinident.de
Katana	Noritake Dental Supply (Aichi, JP)	http://www.noritake-dental.co.jp
Lava™	3M ESPE (Seefeld, US/DE)	http://cms.3m.com/cms/de/de/2-21/ufkren/view.jhtml
Medifacturing®	Bego Medical (Bremen, DE)	http://www.bego-medical.de
MetaNova®	Metanova Dental (Zug, CH)	http://www.metanovadental.com
Precident	DCS (Allschwil, CH)	-
Nanozr*	Panasonic Dental (Osaka, JP)	http://www.panasonic.co.jp/psec/dental
Procera®	Nobel Biocare (Göteborg, SE)	http://www.nobelbiocare.com
Xawex	Xawex (Fällanden, CH)	http://www.xawex.com
Zirconzahn®	Zirkonzahn (Gais, JP)	http://www.zirkonzahn.com

* Ceria stabilized zirconia/alumina nanocomposite.

face damage produced by CAD/CAM milling procedures in combination with different surface treatment methods (ie, grinding) may decrease strength and lead to unexpected failures.[16] In addition, hard and high-temperature milling results in near surface damage and defect formation and can significantly shorten the anticipated life span of the restoration.[17] All current CAD/CAM systems that offer the option for the fabrication of zirconia structures are listed in Table 1.

The spectrum of the contemporary clinical applications of zirconia includes the fabrication of veneers, full and partial coverage crowns or fixed partial dentures (FPDs), posts and/or cores, primary double crowns, implants, and implant abutments. In addition, different zirconia-based auxiliary components such as cutting burs and surgical drills, extra-coronal attachments, and orthodontic brackets are also available as commercial dental products. The purposes of this review are to address current knowledge regarding manufacturing, to highlight the indication spectrum, and to discuss clinical advantages/disadvantages and survivability of zirconia ceramic material in dentistry.

Zirconia single-tooth restorations

Bilayer veneers

Color management of discolored teeth with conventional feldspathic veneers is a rather complicated and technique-sensitive clinical problem.[18] The fabrication of bilayer veneers made from a veneered high-toughness ceramic core is suggested in order to enhance both esthetics and strength.[19-21] The 0.2 mm to 0.4 mm modified core may be fabricated from various high-toughness ceramic materials such as zirconia. In previous studies regarding densely-sintered alumina[22,23] and glass-infiltrated alumina,[24,25] bilayer veneers showed improved color performance on discolored teeth. Therefore, it is assumed that, due to the inherent opacity of the zirconia core,[26,27] the clinical application of zirconia bilayer veneers may offer a high-strength veneer restoration with better masking ability for a given discoloration. No published research data could be found on this topic.

Zirconia crowns

Case selection criteria for zirconia crown restorations (ie, limited interocclusal space, para-functional habits, malocclusion, short clinical crowns, tooth mobility, tooth inclination) and basic clinical sequence do not differ from other all-ceramic crowns (Fig 1). Particularly, tooth preparation clinical guidelines for zirconia crowns are comparable to those for metal-ceramic restorations.[28,29] Appropriate tooth preparation for a zirconia crown should provide favorable distribution of the functional stresses and is usually performed with the use of a specially designed diamond set. In general, tooth preparation for a zirconia restoration requires 1.5 mm to 2.0 mm incisal or occlusal reduction and 1.2 mm to 1.5 mm axial reduction. The axial convergence angle of the crown preparation should be approximately 6 degrees and all dihedral angles should be tapered. The preparation should end with a uniform 0.8 mm to 1.2 mm slight subgingival (approximately 0.5 mm) deep chamfer or marginal shoulder finishing with rounded internal angles. *In vitro* evaluation of the preparation design for zirconia crowns showed significantly higher fracture strength for a circumferential shoulder preparation than other preparation designs due to smaller axial stress concentration. However, for structurally compromised teeth (such as endodontically treated teeth) a slight chamfer preparation was recommended.[30] Regardless of coping thickness, the fracture load required for knife-edge preparations was found to be 38% greater than that required for chamfer preparations.[31] Conversely, imperfections of chamfer preparation by knife-edge finishing tales can put the integrity of the restoration at risk, since they provide a non-uniform cement layer. Under loading, the tensile stresses developed may exceed the bond strength between the cement and the ceramic or tooth, and this, in combination with production flaws or faults, introduced during the cementation process, may lead to fracture initiation.[32] Increase of the axial convergence angle from 6 to 20 degrees may decrease the internal space between the prepared abutment and the zirconia core.[33]

Due to the inherent opacity of zirconia, the abutment should be adequately prepared to allow enough space for both the substructure and the veneering material. After milling, a 0.5 mm-thick uniform zirconia core should be fabricated for single posterior crowns. Particularly in the anterior region, strength and esthetic requirements may allow the fabrication of 0.3 mm-thick copings, however, reduction of the coping thickness from 0.5 mm to 0.3 mm can negatively influence the fracture loading capacity (35% decrease) of zirconia single crowns.[31]

Most systems can accommodate the whitish shade of the raw zirconia framework before sintering by a close to the final shade staining. This shading possibility may also be useful in cases of limited interocclusal space where veneering is limited or omitted.

Zirconium oxide crowns may be cemented using both conventional and adhesive methods (compomers, resin-modified glass-ionomers and self-adhesive composite resin cements) that provide comparable bonding strength with the composite resin cements.[34,35] However, a strong and durable resin bond provides high retention, improves marginal adaptation, prevents microleakage, and increases the fracture resistance of the restored tooth and the restoration. Previous knowledge regarding the adhesion of luting agents and silica-based ceramics cannot be used for resin bonding to Y-TZP. Surface pretreatments used for glasses (ie, hydrofluoric acid etching, silanization) do not im-

Fig 1 A total of 12 maxillary single zirconia crowns (teeth 16 to 26). Top: full coverage preparation of the abutment teeth (palatal aspect). Middle: zirconia frameworks (ZENO Tec®, Wieland, Pforzheim, Germany) *in situ* (palatal aspect). Bottom: final clinical situation after crown adhesive cementation (palatal aspect). Clinical and laboratory work performed by Dr S Pelekanos and Mr V Mavromatis (both Athens, Greece), respectively.

Fig 2 Anterior six-unit zirconia fixed partial denture restoration (teeth 13 to 23). Top: zirconia framework *in situ* (palatal aspect). Middle: zirconia framework (ZENO Tec, Wieland) after laboratory completion. Bottom: final clinical situation after adhesive cementation of the restoration (palatal aspect). Clinical and laboratory work performed by Dr SO Koutayas (Corfu, Greece) and Mr E Blachopoulos (Athens, Greece), respectively.

prove the bonding strength of zirconium ceramics because of the high crystalline content that cannot be modified by etching.[36] In contrast to grinding, which may lead to substantial strength degradation, sandblasting seems to strengthen Y-TZP[37] and improve bonding.[37-40]

It was demonstrated that the application of the adhesive phosphate monomer 10-methacryloyloxydecyl dihydrogen phosphate (MDP)[41] or an MDP-containing bonding/silane coupling agent mixture[42] after airborne- particle abrasion (110 μm Al_2O_3 at 2.5 bar) and a phosphate-modified resin cement (eg, Panavia™ 21, Kuraray, Osaka, Japan) may provide a long-term durable resin bond to zirconium oxide ceramic[38] with promising high tensile bond strengths (39.2 MPa).[43] Furthermore, it was shown that the application of a tribochemical silica coating (eg, CoJet™, 3M ESPE, Seefeld, Germany) in combination with an MDP-containing bonding/silane coupling agent mixture increased the shear bond strength between zirconium-oxide ceramic and phosphate-modified resin cement (Panavia F, Kuraray).[44] The tribochemical silica coating process was also tested with zirconia silanization (N.B. prefabricated zirconia posts), which resulted in an increased bond strength.[45] Moreover, a self-curing dental adhesive system containing 4-META/MMA-TBB (eg, Superbond C&B, Sun Medical, Tokyo, Japan) exhibited high bond strengths regardless of the different surface treatments such as silica coating, airborne particle abrasion, hydrofluoric acid (HF) etching and diamond grinding.[46] It was illustrated that the bond strength of bis-GMA resin cement (eg, Variolink® II, Ivoclar Vivadent, Schaan, Liechtenstein) to the zirconia ceramic can be significantly increased after pre-treatment with plasma spraying (hexamethyldisiloxane) or by the use a low-fusing porcelain layer.[47]

Regardless of surface pre-treatments, long-term *in vitro* water storage and thermocycling can negatively influence the durability of the resin bond strength to zirconia ceramic.[41] Thermocycling induces a higher impact than water storage at a constant temperature.[48] It is essential to avoid contamination of the zirconia bonding surfaces during try-in procedures, either by saliva contact or by a silicone disclosing medium. It was found that air abrasion with 50 mm Al_2O_3 at 2.5 bar for 15 s is the most effective cleaning method to regain an optimal bonding surface.[49,50]

The clinical application of zirconia crowns in removable prosthodontics is a new approach, implemented either as a crown with guide planes and rest seats[51] or as a primary crown for double crown systems.[52,53] Particularly in double crown systems, the secondary crowns are preferably fabricated with galvano-forming technology.[53] Despite the excellent wear resistance and biocompatibility of the primary zirconia crown, the colored zirconia copings are a solution to the esthetic compromise of marginal metal exposure.

Zirconia fixed partial dentures

Based on the exceptional mechanical properties of zirconia (eg, high flexural strength and fracture resistance),[54,55] Y-TZP is the most recent framework material for the fabrication of all-ceramic FPDs either in anterior (Fig 2) or posterior sites (Fig 3).[56-59] The load bearing capacity of Y-TZP FPDs was found to be significantly higher than

Fig 3 Posterior four-unit zirconia fixed partial denture restoration (teeth 47 to 44). Top: zirconia framework *in situ* (occlusal aspect). Middle: zirconia framework (ZENO Tec, Wieland) after laboratory completion. Bottom: final clinical situation after adhesive cementation of the restoration (occlusal aspect). Clinical and laboratory work performed by Dr S Pelekanos and Mr V Mavromatis (both Athens, Greece).

Table 2 Clinical studies on zirconia-based fixed partial dentures (FPDs).

Author	Year	System	Zirconia FPDs		Units		Duration	Fractures (%)	Chipping (%)
			Anterior	Posterior	3	> 3	(years)	(core)	(veneering)
Sturzenegger[83]	2000	Direct ceramic machining	-	21	21	1	1	0.0	0.0
Pospiech[88]	2003	Lava™	-	38	38	0	1.5	0.0	2.5
Bornemann[89]	2003	Cercon®	-	59	44	15	1	0.0	4.3
von Steyern[71]	2005	Precident	3	17	2	18	2	0.0	15.0
Sailer[86]	2006	Direct ceramic machining	-	57	N.R.	N.R.	3	0.0	13.0
Raigrodski[87]	2006	Lava™	-	20	20	0	3	0.0	15.0
Sailer[82]	2007	Direct ceramic machining	-	33			5	2.2	15.2
Edelhoff[90]	2008	Digident®	4	18	14	8	3	0.0	9.5
Tinschert[84]	2008	Precident	15	50	44	21	3	0.0	6.1
Molin and Karlsson[85]	2008	Cad.esthetics®	0	19	19	0	5	0.0	0.0*
Roediger[91]	2009	Cercon®	-	99	N.R.	N.R.	4	1.0	13.1

N.R., not referred to; * 30% slightly rough or pitted occlusal surfaces.

other conventional all-ceramic systems, such as lithium-disilicate glass ceramics and zirconia-reinforced glass-infiltrated alumina,[60] and it has been reported that fracture resistance was further increased after veneering.[61]

Zirconia-based FPDs may exhibit a good long-term prognosis if connectors are properly designed and fabricated.[62] Finite element stress analysis studies on three-unit posterior FPDs showed that maximum tensile stresses occur on the gingival site of the connector between the two abutments, and the magnitude significantly depends on the loading conditions, shape, and size of the connector.[63-65] Furthermore, it has been observed that when zirconia FPDs are subjected to the peak of tensile stresses, the properties of the feldspathic porcelain, used for veneering of high-toughness core materials, may control the failure rate of the restoration.[66,67] Research shows that ultimate strength can be achieved by omitting porcelain veneering at the gingival surface of the connectors.[68,69,70] Calculations, based on the fatigue parameters, indicate that connector dimensions should be at least 5.7 mm^2, 12.6 mm^2, and 18.8 mm^2, for the fabrication of a 3-, 4-, or 5-unit FPD, respectively.[56] It was recommended that the connector size should be larger than 7.3 mm^2, especially for the clinical application a 4-unit posterior Y-TZP FPD.[60] *In vitro* evaluation of Y-TZP FPDs with smaller connectors (3.0 mm x 3.0 mm) also revealed good fracture resistance results.[71-73] Moreover, a minimum diameter of 4.0 mm for all-ceramic zirconia-based FPDs with long spans or replacing molars has been recommended.[74] Since connector dimensions and geometry are crucial for the appropriate stability of the restoration under functional loading, the designing features of the framework must be optimized in order to reinforce the connector areas and provide the adequate support to the veneering material (note framework design in Figs 2 and 3). The marginal fit of most zirconia-based FPDs fabricated with CAD/CAM technology meets clinical requirements.[61,75,76] However, regardless of the CAD/CAM system, the marginal adaptation is influenced by framework configuration.[76]

After fabrication, Y-TZP frameworks are relatively opaque and white in color;[77] therefore the compatible feldspathic porcelain veneering material is essential to achieve good esthetics. Literature data are rather contradictory regarding the effect of surface pre-treatment (ie, grinding, sandblasting) on the strength characteristics of Y-TZP frameworks. Moreover, during the veneering procedure the frameworks are exposed to high temperatures and moisture, which may cause a mechanical property degradation of the restoration.[78-81]

Short-term clinical data showed that Y-TZP FPDs have a promising survival time for anterior as well as posterior regions (Table 2).[71,82-91] However, the available clinical studies (see Table 2), with an observation period of up to 5 years, disclosed chipping of the veneering material as a major problem that might occur increasingly over time (15.2%). The overall fracture rate of the zirconia frameworks were relatively low (up to 2.2%).[82] Fractographic analyses of retrieved zirconia FPDs showed that primary fractures initiated from the gingival surfaces of the connectors to the veneering surfaces while delamination of the ceramic structures in the veneering/ zirconia core interface was controlled by secondary fracture initiation sites and failure stresses.[92] Implant-supported Y-TZP FPDs have also exhibited an unacceptable amount of veneering chipping either *in vitro*[71] or *in vivo*.[93]

As an alternative to complete coverage, partial-coverage resin-bonded zirconia FPDs (RB-Z-FPDs) were introduced as less invasive treatment options for both the anterior and the posterior regions. The par-

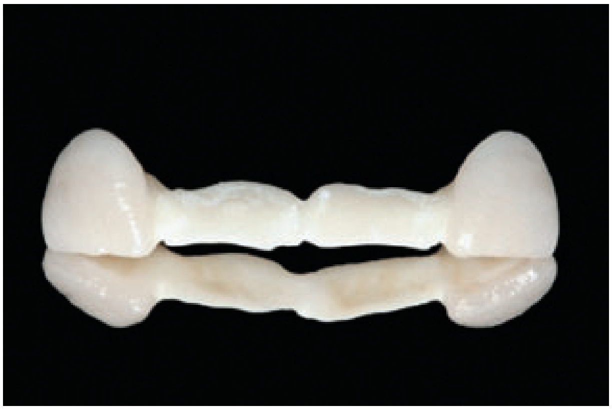
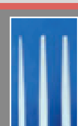
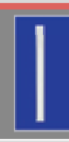
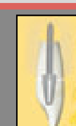
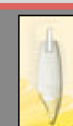


Fig 4 Anterior cantilevered zirconia resin-bonded FPD (teeth 11 and 21). Top: zirconia framework (ZENO Tec, Wieland) *in situ* (occlusal aspect). Middle: zirconia RB-FPD after veneering. Bottom: final clinical situation after adhesive cementation of the restoration (occlusal aspect). Clinical and laboratory work performed by Dr SO Koutayas (Corfu, Greece) and Mr E Blachopoulos (Athens, Greece), respectively.

Table 3 Overview of current zirconia implants.

	1995	1998	2001	2005		2005		2006
								
Manufacturer	Gebr. Brasseler	Ivoclar Vivadent	Cendres+Métaux	atec Dental		Incermed		Nordin Dental
Website	http://www.kometdental.de	http://www.ivoclarvivadent.com	http://www.cmsa.ch	http://www.atec-dental.de		http://www.incermed.ch		http://www.nordin-dental.com
Name	CeraPost	CosmoPost	CM	Endofix®	Endoseal/WSR	Biopost	Biosnap	Zirix®
Material	ZrO_2	ZrO_2	ZrO_2	ZrO_2	ZrO_2	ZrO_2	ZrO_2	ZrO_2
Color	opaque/ whitish	opaque/ whitish	opaque/ whitish	opaque/ whitish	opaque/ whitish	opaque/ whitish	opaque/ whitish	opaque/ whitish
Type	conical	cylindrical /conical	cylindrical /conical	cylindrical /tipped	conical	cylindrical /conical	cylindrical /conical	cylindrical /conical
Surface (micro/macro)	smooth	smooth	smooth	smooth/ screwed	smooth	smooth/retent. slot	smooth	smooth/ screwed
Diameter (mm)	0.5, 0.9, 1.1	1.4, 1.7	1.4, 1.7	1.3, 1.5, 1.7, 1.9	1.3, 1.5	1.1, 1.3, 1.4, 1.5, 1.6, 1.7	1.5, 1.6, 1.7	1.10, 1.25, 1.35, 1.50
Length (mm)	12	20	17, 20.5	20	6	11, 14	11	25 to be measured
Remarks	direct / indirect restoration	direct / indirect restoration	direct restoration	transfixation screw-post	seal after apicoectomy	direct restoration	ball attachment Ø (mm): 2.5–3.0	direct restoration

tial coverage retainers of these restorations can be single (or, rarely, double) palatal veneer retainers (wings),[94] partial crowns, inlays, or onlays.[95] It has been demonstrated that aluminum oxide anterior cantilever resin-bonded fixed partial dentures with specific design features of the connectors, can successfully withstand physiological incisive forces for five years both *in vitro*[96] and *in vivo*.[97,98] If the fact that the zirconia connector exhibits improved strength is taken into consideration, it is assumed that RB-Z-FPDs have the potential to produce better clinical performance than the aluminum oxide ones (Fig 4).

Regarding inlay-retained zirconia FPDs (IR-Z-FPDs), compressive mechanical testing showed high fracture resistance.[99–101] Considering the maximum chewing forces in the molar region, it was proposed that the connector size should be between 9 mm^2 and 16 mm^2.[101] In order to improve strength performance of IR-Z-FPDs, clinical trials indicated new preparation and framework designs with the following main features: *a)* 1-mm shallow occlusal inlay, *b)* 0.6-mm oral retainer wing, and *c)* non-veneered retainer.[101] Conversely to RB-Z-FPDs, long-term clinical studies on IR-Z-FPDs are needed before their extensive clinical application.

Zirconia posts

A metal post and core system restricts light transmission and thus gives an undesirable dark shadow in the root and cervical areas, especially through thin periodontal tissues[102] and significantly decreases the value of the coronal part of the restoration.[103] With the introduction of custom-made all-ceramic posts and cores[104-106] or zirconium dioxide (ZrO_2) prefabricated posts,[107,108] a unique esthetic approach has been developed in combination with all-ceramic crowns. Dentin-like shade all-ceramic posts and cores contribute to a deeper diffusion of light and therefore provide an appropriate depth of translucency.[109,110]

Contemporary zirconia powder technology contributes to the fabrication of new biocompatible and esthetic endodontic posts with improved flexural strength (approximately 820 MPa) and fracture toughness (approximately 8 MPa*$m^{1/2}$). As an additional indication, zirconia endodontic endosseous cones seem to be acceptable for sealing purposes in resected teeth after apicectomy.[111] Current commercially available zirconia post systems are listed in Table 3.

The placement of a prefabricated post (ie, zirconia post) is usually unnecessary for intact endodontically treated teeth (without proximal cavities), where only the access opening should be sealed with hybrid composite.[112] The clinical application of zirconia posts in teeth with small tooth structure defects can be exercised, in conjunction with hybrid composites or special built-up composites, according to the concepts of contemporary adhesive dentistry.[113] If adequate sound coronal tooth structure is present, all-ceramic posts and cores also can be viable following two fabrication techniques: direct or indirect application.[96,114] According to the two-piece technique, a ceramic core (ie, zirconia core) formerly fabricated with the use of a copy-milling machine (ie, Celay system, Mikrona, Spreitenbach, Switzerland) or today using CAD/CAM technology, is placed onto the prepared tooth, and then a prefabricated ZrO_2 post (eg, CeraPost, Gebr. Brasseler, Lemgo, Germany) is adhesively

Fig 5 Single crown restoration of a maxillary left endodontically treated lateral incisor (tooth 12) with the use of an all-zirconia post and core (Courtesy Prof RJ Kohal, Freiburg, Germany): **a)** initial situation after endodontic treatment (labial aspect), **b)** prefabricated zirconia post (CeraPost, Gebr. Brasseler) with core analogue model, **c)** two-piece all-zirconia post and core after copy-milling (Celay system, Mikrona) of a Y-TZP core (BCE, Mannheim, Germany), **d)** bonding of the post and core restoration using an adhesive resin (Panavia 21, Kuraray), **e)** completion of the tooth preparation, **f)** final clinical situation after crown placement (Empress, Ivoclar Vivadent). Laboratory work performed by Mr F Ferraresso (Saluzzo, Italy) and Dr SO Koutayas (Corfu, Greece).

cemented into the root canal through the canal of the core (Fig 5). Moreover, according to the heat-pressing technique, a glass-ceramic core (EmpressCosmo, Ivoclar Vivadent) is heat-pressed over a prefabricated ZrO_2 post (eg, CosmoPost, Ivoclar Vivadent), so that both materials are integrated to a unified and solid post-and-core-restoration.

After placement of the zirconia posts and cores for the pre-prosthetic management of the remaining abutment tooth structure, anterior endodontically treated teeth may be successfully restored with single all-ceramic crowns and withstand functional incisive forces.[115-118] Additional *in vitro* testing identified the incidence of root fractures,[119,120] however, short-term clinical evaluation of zirconia posts and/or cores were promising.[121,122] A 4-year retrospective study showed that single crown restorations using prefabricated ZrO_2 posts with indirect glass-ceramic cores displayed a significantly higher failure rate than using the same posts with direct composite build-ups.[123]

The clinical application of zirconia posts is an almost irreversible procedure since their removal is extremely difficult.[114] Essentials for achieving clinical longevity are tooth preservation during root canal preparation and maintenance of both the appropriate ferrule effect (minimum 2 mm in height)[124,125] and the periphery of the root canal dentin (minimum 1 mm in width).[125] Zirconia posts display a higher modulus of elasticity (200 MPa) than natural dentin (16.5 to 18.5 MPa); in the absence of the ferrule effect, catastrophic stresses can be transferred to the root.[119,120,126] Adhesive cementation of such rigid posts might also present interfacial defects within the built-up composite or the dentin.[127] Due to the above-mentioned limitations, a systematic review concerning the biomechanics of endodontically restored teeth suggested the use of post-and-core materials with physical properties close to those of natural dentin.[128,129]

Zirconia implants

Titanium release after implant placement[130,131] intensified the discussion regarding sensitization or allergies,[132,133] which subsequently stimulated holistic approaches that embrace metal-free implant dentistry. However, the main practical disadvantage of titanium implants is the management of the grayish appearance through thin peri-implant mucosa. All of the above have oriented dental research and propelled the clinical application of implants made from different novel ceramic biomaterials such as single- and polycrystal alumina,[134] bioactive glasses,[135] hydroxidapatite,[136] and zirconia (Fig 6).[137-139] Furthermore, zirconium oxide coatings (approximately 100 nm) of Ti-6Al-4V,[140] or titanium[141] orthopedic implants, usually after the application of macro-texturing methods,[142] may promote bone growth and thus provide evidence of enhanced implant osseointegration.

Y-TZP is currently considered an attractive and advantageous endosseous dental implant material because it presents enhanced biocompatibility, improved mechanical properties, high radiopacity, and

Fig 6 Zirconia implant supported zirconia crown (tooth 12) (Courtesy Prof RJ Kohal, Freiburg, Germany). Top: zirconia implant placement after tooth extraction. Middle: 4 months later; placement of retraction cord prior to impression. Bottom: after final cementation of zirconia crown (Procera, Nobel Biocare). Laboratory work performed by Mr W Woerner (Freiburg, Germany).

easy handling during abutment preparation.[143,144] Zirconia ceramic is well-tolerated by bone and soft tissues and possesses mechanical stability.[145] Since the difference in bone-to-implant attachment strength between bio-inert ceramics and stainless steel was not significant, it was indicated that the affinity of bone to bio-inert ceramics has almost the same capacity as metal alloys.[146]

In vitro culture tests were performed to verify biocompatibility, genetic effects, and osteoblast interactions of potential zirconia implant substrates. Recently, a series of well-reviewed studies[147] showed no adverse response,[148,149] surface-specific[150,151] and non-surface-specific[149] proliferation, attachment and spreading of osteoblasts, and no genetic effect of zirconia on bone formation.[152-154]

Animal studies that focused on zirconia implants without loading demonstrated comparable qualitative and quantitative characteristics to that of the titanium implants in biocompatibility and osteoinductivity.[155-158] *In vivo* studies proved that micro-modification of Y-TPZ implants, resulting in a roughened surface, was beneficial for initial bone healing, bone apposition, and interfacial shear strength.[158,159] Additional animal studies confirmed that Y-TZP and Ti implants can be successfully osseointegrated under loading conditions, however, one research group noted a relatively high marginal bone loss[160] while a second group reported similar soft tissue peri-implant height.[138]

Different *in vitro* studies were performed to define the feasibility of zirconia implant systems. A finite element assessment of the loading resistance revealed non-distractive and well-distributed stress patterns, similar to those of titanium implants.[161] Furthermore, it was proposed that one-piece zirconia implants restored with densely sintered alumina crowns (Procera®, Nobel Biocare, Göteborg, Sweden) could possibly fulfil the biomechanical requirements for anterior tooth replacement. Regarding the impact of the design (one or two pieces) on the biomechanical behavior of Y-TZP implants using chewing simulation testing conditions, a prototype two-piece zirconia implant revealed low fracture resistance at the level of the implant head and therefore questionable clinical performance,[162] while one-piece zirconia implants seem to be clinically applicable.[163] Moreover, it was illustrated that preparation of the one-piece zirconia implant in order to accept a crown had a statistically significant negative influence on the implant fracture strength.[163]

To date, there are five commercially available zirconia implant systems on the market (listed in Table 4). Only one system (Sigma, Incermed, Lausanne, Switzerland) provides both one- and two-piece designs while all the other (CeraRoot, CeraRoot Dental Implants, Barcelona, Spain; Z-Look3, Z-Systems, Constance, Germany; whiteSKY, Bredent Medical, Senden, Germany, and zit-z, Ziterion, Uffenheim, Germany) are available in a one-piece design. Furthermore, a recent clinical trial described a type of customized zirconia root-analogue implant with a micro- and macro-retentive implant surface, however, neither the zirconia material nor the milling device were specified.[164]

Despite some promising preliminary clinical results, no clinical long-term data are available concerning zirconia implants. Survival rates after one year were reported at 93% (189 one-piece implants, Z-Systems),[165] 98% (66 one-piece implants, Z-

Systems),[137] and 100% (one-piece implants, CeraRoot).[166] Furthermore, a recently published review noted that in an ongoing clinical study, TZP-A (ZrO_2/Y_2O_3/Al_2O_3) experimental implants (n=119) with an especially roughened surface presented a survival rate of 96.6% after a 1-year observation period.[147] Finally, the only systematic review that explored the osseointegration and the clinical success of zirconia dental implants confirmed that Y-TZP implants can be osseointegrated to the same extent as titanium ones. Nevertheless, clinical and laboratory research data were scarce on safe recommendations for a widespread clinical application of Y-TZP implants.[167]

Zirconia implant abutments

In modern implant dentistry, high survival rates for implants and implant-supported single crowns can be expected.[168] Concerning the esthetic outcome, conventional metal (titanium) abutments do shimmer, especially through all-ceramic crowns with increased semi-translucency and, subsequently, through thin peri-implant mucosa, resulting in a grayish appearance of the entire restoration.[169] Thin periodontal biotypes cannot mask this negative effect, nor guarantee a long-lasting architectural stability of the peri-implant tissue.[170-172] These esthetic problems, or the possible exposure of the underlying metal abutment which may be visually perceivable, can be accommodated by the clinical application of all-ceramic abutments.[147,173]

All-ceramic implant abutments made from aluminum oxide ceramic material (glass infiltrated or densely sintered alumina) were first introduced as an esthetic alternative to titanium ones in the mid-1990s.[174-176] The alumina abutments presented pleasing optical properties,[177] adequate fracture strength for the anterior regions,[178] and an excellent 5-year prognosis.[179] However, implant manufacturers have turned their production to abutments made from zirconia (Fig 7).[169] Besides strength considerations, Y-TZP implant abutments offer enhanced biocompatibility,[1] metal-like radiopacity for better radiographic evaluation,[180] and, ultimately, reduced bacterial adhesion,[181] plaque accumulation,[182] and inflammation risk.[183] Moreover, Y-TZP abutments may promote soft tissue integration,[184] while favorable peri-implant soft tissues may be clinically achieved adjacent to zirconia[185] or alumina-zirconia abutments[186] and zirconia healing caps.[187] A systematic review revealed that zirconia abutments could maintain an equivalent bone level in comparison to titanium, gold, and aluminum oxide ones.[188] *In vitro* examination of the cellular attachment, spreading and proliferation of human gingival fibroblasts to milled and polished non-veneered ceramic surfaces showed significant differences associated with the various surface modifications, requiring further investigation and documentation for clinical extrapolation.[189]

Y-TZP abutments are available in two types: prefabricated and custom-made. Prefabricated zirconia abutments are a reliable and practical solution, but CAD/CAM technology is also beneficial in designing fully individualized zirconia abutments for ideal soft-tissue integration and esthetics. Both types of abutments give the opportunity for further customization either by extra-oral or intra-oral preparation using special water-cooled cutting di-

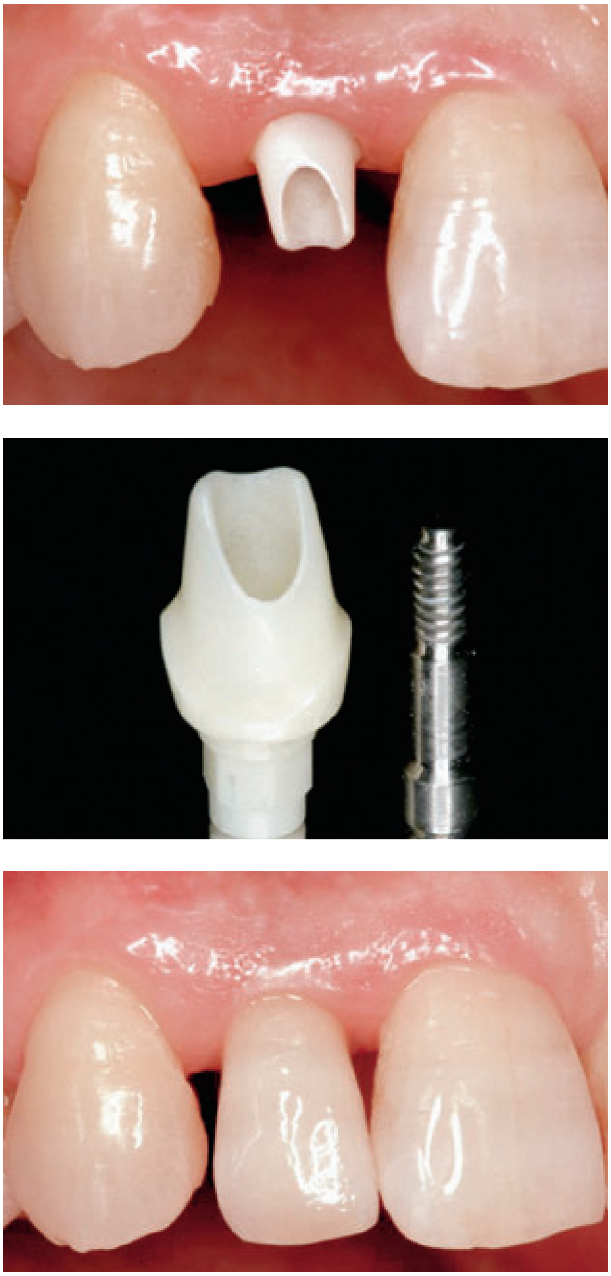
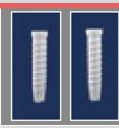
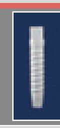
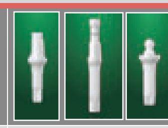
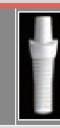
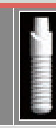
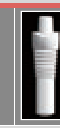
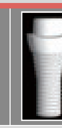


Fig 7 Single implant all-ceramic crown restoration (VITA® In-Ceram SPINELL, Vident, Brea, CA, USA) with the use of a zirconia prefabricated abutment (Cercon® for XiVE, Dentsply Friadent, Mannheim, Germany) of an upper right lateral incisor (tooth 12). Top: abutment connection (labial aspect). Middle: zirconia abutment after laboratory modification and Ti screw. Bottom: final clinical situation after crown adhesive cementation (labial aspect). Clinical and laboratory work performed by Dr SO Koutayas (Corfu, Greece) and Dr D Charisis (Athens, Greece), respectively.

amonds indicated by the manufacturer. Representative prefabricated and custom-made Y-TZP abutments are shown in Table 5. According to the knowledge of the authors, additional Y-TZP implant abutments are also commercially available from the following companies: Thommen Medical (SPI® ART abutment), Camlog (Esthomic ceramic abutment), Zimmer Dental (Contour ceramic abutment), Dentaurum Tiolox Implants (Tiolox® Premium), Wieland Dental Implants (wi.tal ceramic abutment), Sybron Implant Solutions (CAD/CAM-base post), Cad.esthetics (Denzir implant post).

Concerning abutment custom preparation, cutting efficiency and finishing by different diamond types were explored and the achieved effects were specified for certain kinds of abutments, indicating that achieving the best finish lines and surfaces may require the use of specific cutting instruments and protocols.[144] Most manufactures recommend either a pronounced chamfer or a shoulder preparation with rounded inner line angles. Moreover, subgingival margins should not be overextended beyond the point that removal of permanent cement presents difficulties and, generally, the emergence profile should be rather concave and must follow known diagnostic regimens.[173] Recently, it was shown that adhesively luted single implant anterior crowns to zirconia abutments with a 0.5 mm to 0.9 mm deep circumferential chamfer preparation have the potential to successfully serve for more than five years of simulated fatigue.[190] Marginal adaptation of zirconia abutments can be achieved either by the abutment itself or by a titanium integrated post and an occlusal screw.[191] *In vitro* fit evaluation of internal or external hexagon CAD/CAM cus-

Table 4 Overview of current zirconia implants.

	2002				2004	2004					2007	2006
												
Manufacturer	Incermed				Z-Systems	CeraRoot					Bredent	Ziterion
Website	http://www.incermed.ch				http://www.z-systems.biz	http://www.ceraroot.com					http://www.bredent-medical.com	http://www.ziterion.com
Name	Sigma				Z-Look3	CeraRoot					whiteSKY	zit-z
	bivalent millenium	polyvalent				11	21	12	14	16		
Material	HIP ZrO_2/TZP				HIP ZrO_2/TZP	HIP ZrO_2/TZP					HIP ZrO_2/TZP	HIP ZrO_2/TZP
Color	whitish				whitish	whitish					whitish	whitish
Type	two-piece design	one-piece design			one-piece design	one-piece design					one-piece design	one-piece design
Diameter (mm)	3.4, 3.7, 4.28	3.4	3.7	4.28	3.5, 4.0, 5.0	4.8/6.0/6.5	4.1/4.8/6.0	4.1	3.5/4.8/5.8	4.8/6.5/8.0	3.5, 4.0, 4.5	
Length (mm)	11.6, 14.4	14.5, 16.7, 18.5	13.7, 16.5	14.0, 16.8	10.0, 11.5, 13.0	10.0, 12.0, 14.0	10.0, 12.0, 14.0	10.0, 12.0, 14.0	10.0, 12.0, 14.0	10.0, 12.0, 14.0	10.0, 12.0, 14.0,	
Remarks	transgingival height: 1.52 mm	abutment height 2.98–3.28 mm transgingival height: 0.93 mm			narrow neck D3.6N reduced shoulder D4.0R ball attachment D 4.0/Ø 2.9	root form, scalloped shoulder						transgingival height: 1.5, 2.5 mm

tom abutments met clinical requirements[192] and hexagonal external connections showed less than three degrees of rotational freedom.[193] Screw joint designs as shown in previous studies[194,195] or loosening implications due to a poor fit at the implant/abutment interface should be avoided through appropriate laboratory processing.[196] Generally, Y-TZP implant abutments revealed three-times higher fracture strength than abutments made out of aluminum oxide ceramic.[197] *In vitro* testing of CAD/CAM-processed, implant-supported single crowns by either prefabricated[178,198,199] or customized[81] Y-TZP abutments showed that they can resist physiologic incisive forces. Finally the results of the laboratory studies performed in a mastication simulator[178,198,199] were confirmed by clinical studies that reported cumulative survival rates of 100% after 6 years of clinical service. However, due to the limited number and the moderate observation time of the existing clinical studies, further long-term evaluation is necessary.[167,188]

Zirconia dental auxiliary components

Orthodontic brackets

Currently available ceramic polycrystalline zirconia brackets offer some advantages over traditional ones. Y-TZP orthodontic brackets provide enhanced strength, superior resistance to deformation and wear, reduced plaque adhesion, and improved esthetics. In addition they exhibit good sliding properties with both stainless steel and nickel-titanium arch wires and the same frictional characteristics as polycrystalline alumina brackets.[200,201] Clinically, they present acceptable bond strengths using light-cured adhesives, however, the location of bond failure is detected at the bracket/adhesive interface.[202,203] Shear-strength forces at failure were also found within clinical acceptance and significantly higher than those of metal brackets.[204] Conversely, Y-TZP orthodontic brackets, in comparison with the metal ones, may exhibit reduced efficiency regarding tooth movement,[205,206] enamel damage due to high debonding rate,[207] severe enamel wear to the opposing dentition,[208] and an off-white, highly opaque appearance.[202]

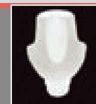
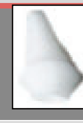
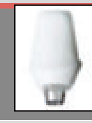
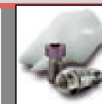
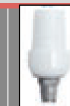
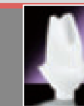
Precision attachments

The clinical application of prefabricated zirconia attachments is based on the wear and strength characteristics of the material. However, there is no literature available regarding either clinical performance or effectiveness. Two different types of Y-TZP attachments are currently on the market: a ball attachment for overdentures as a part of a zirconia post (Biosnap, Incermed) available in three diameters for three levels of retention (Table 3) and an extracoronal, cylindrical, or ball attachment for removable partial dentures (Proxisnap, Incermed).

Cutting and surgical instruments

Newly developed zirconia cutting instruments (ie, drills, burs) can be used in implantology, maxillofacial surgery, operative dentistry, and soft tissue trimming (eg, CeraDrill™ CeraBur™ K1SM CeraBur™ Ceratip, respectively, all Gebr. Brasseler). These instruments offer optimal cutting efficiency with smooth operation and reduced vibration while their proven resistance to chemical corrosion promises a long-lasting performance. Finally, surgical

Table 5 Overview of prefabricated and customized Y-TZP implant abutments.

	2001	2005	2002		2001	2001	2007	2002	2005	2003
										
Manufacturer	Dentsply Friadent	Dentsply Friadent	Nobel Biocare		Straumann	Biomet 3i		Bego	Astra Tech	Astra Tech
Website	http://www.friadent.de	http://www.friadent.de	http://www.nobelbiocare.com		http://www.straumann.com	http://www.biomet3i.com		http://www.bego.com	http://www.astratechdental.com	http://www.atlantiscomp.com
Name	Cercon® balance	Friadent Cercon®	Procera™ abutment zirconia	Procera™ abutment zirconia for other implants	RN synOcta® custom abutment (cares)	external hex ZiReal® post	Certain® ZiReal post	BeCe® sub-tec ceramic	ZirDesign™	Atlantis™
Material	Y-TZP	Y-TZP	Y-TZP	Y-TZP Ti seating post	Y-TZP Ti seating post	Y-TZP Ti seating ring or post		Y-TZP	Y-TZP	Y-TZP
Color	whitish	whitish, dentin	whitish	whitish	whitish	whitish		whitish	whitish	whitish
Connection	internal cone Ti screw	internal hex Ti screw	external hex Ti screw	internal hex Ti screw	internal hex (synOcta® 1.5) Ti screw	external hex au-screw	internal hex au-screw	internal cone & hex & Ti screw	internal cone & hex & Ti screw	internal hex or external hex & system screw
Implant diameter (mm)	Ankylos® 5.5, 7.0	XiVE 3.8, 4.5	all Brånemark NP/RP/WP (*)	NobelReplace™ NP/RP/WP Straumann RN 4.8, camlog 3.3 to 6.0	Straumann RN 4.8	NanoTite™ Osseotite NT®, pw, xp 4.1, 5.0	NanoTite™ Osseotite Certain® 4.1, 5.0	Bego S 3.25–5.5 Bego RI 3.75–5.5	OsseoSpeed™ 3.5/4.0, 4.5/5.0	internal hex implant (**) external hex implant (***)
Gingival height	1.5, 3.0 scalloped	1.0, 2.0	customized		customized	4.0			1.5, 3.0 scalloped	customized
Inclination	straight (0º), angled (15º)	straight (0º), angled (15º)	customized		customized	straight (0º) angled (17º)		straight (0º)	straight (0º), angled (20º)	customized
Type	prefabricated	prefabricated	customized (Procera™ 3-D CAD)		customized (Sirona inlab)	prefabricated		prefabricated	prefabricated	customized (Atlantis™ VAD)

(*) Lifecore Biomed:. Restore 3.75, Zimmer Dental: Taperlock 4.0, Sterngold: Implamed 3.75, Biomet 3i: 3.75.
(**) Astra Tech: OsseoSpeed™ 3.5/4.0, 4.5/5.0 – BioHorizons: Internal 3.5, 4.5, 5.7 - Biomet 3i: Certain™ MicroMiniplant™ 3.25/3.4, Certain™ 3.75/4.0, 5.0, 6.0, XP 4/5, XP 5/6 - Nobel Biocare: NobelReplace™ NP (3.5), RP (4.3), WP (5.0, 6.0) – Straumann: Standard/Standard Plus Implant RN (Regular Neck) 4.8 - Zimmer Dental: Tapered Screw-Vent™ 3.5, 4.5, 5.7, Screw-Vent™ 3.5, 4.5, SwissPlus™ 4.8.
(***) BioHorizons: External 3.5, 4.0, 5.0 - Biomet 3i: MicroMiniplant™ 3.25/3.4, Miniplant™ 4.1/3.25, Standard 3.75, 4.0, Wide 5.0, 6.0, XP 3/4, 4/5, 5/6 - Sybron Implant Solutions: Innova Endopore 3.5, 4.1, 5.0, Innova Entegra 3.5, 4.1, 5.0 - Lifecore Biomed: Small 3.3, 3.4, Regular 3.75, 4.0, Wide 5.0, 5.5, 6.0 - Nobel Biocare: Brånemark System™ NP (3.3), RP (3.75, 4.0), WP (5.0, 5.5), Nobel Biocare: SteriOss Replace™ 3.1, 3.5, 4.3, 5.0, 6.0, SteriOss HL™ 3.25, 3.8, 4.5, 5.0, 6.0.

instruments such as scalpels, tweezers, periosteal elevators, and depth gauges can be made out of alumina-toughened zirconia (ATZ) by injection moulding (Z-Look3 Instruments, Z-Systems).

Discussion

Technology has many origins that include a combination of inspiration, fortuitous events, and basic research. After the discovery of the toughening transformation potential of zirconia in the mid-1970s,[209] ample progress has been made in dental science regarding ceramic materials. Today, zirconia technology has become the cynosure of the research and clinical efforts of an increasing number of dental scientists. Industrial development of more than 20 different CAD/CAM systems (Table 1) concerning zirconia manufacturing indicates an increasing clinical interest and fosters the firm conviction that zirconia could become the star of dental restorations.[210,211] According to research of manufacturers, the clinical spectrum of zirconia-based restorations appears impressive and embraces practically every restorative aspect including veneers, crowns, FPDs, posts, implant abutments, and even implants. In 2006 more than 100 metric tons of medical grade ZrO_2 raw material was processed worldwide, while in 2008, 250 tons were expected.[212] This increased and conspicuous consumption of zirconia for dental applications signifies that zirconia-based restorations with the support of computerized systems will be of utmost importance in the dental profession in the coming years.

Current *in vitro* research, performed to understand the nature of the technology, included cell, thermal fatigue, colorimetric, marginal fit, fracture strength, and bonding studies. *In vitro* results are promising, especially in all aforementioned fields, however, since clinical research focuses on how technology affects humans and other living organisms, extensive clinical application of the zirconia technology should await confirmation through cohort longitudinal clinical studies. Despite the known high biocompatibility of zirconia in both soft and hard tissues, dental zirconia restorations are slowly moved from the controlled experimental setting to the clinical environment and some clinical studies of up to five years can be found in the literature. Existing studies evaluated clinical parameters (eg, fit, color performance, survival rates) and determined the frequency of adverse effects (eg, chipping, fractures, debonding), mainly regarding the clinical application of zirconia FPDs and posts.[213,214] Material-specific phase transformation, particularly from the tetragonal to the monoclinic crystal phases, inhibits crack propagation and results in the superior mechanical performance of zirconia. Therefore, zirconia frameworks obtain excellent physical properties such as high strength and fracture toughness.[209] Conversely, during aging in an aqueous oral environment, spontaneous phase transformations of the tetragonal zirconia to monoclinic phase, known as low temperature degradation (LTD), could lead to the formation of microcracks and subsequently to a decrease in strength.[215,216] This problem mainly involves frameworks or parts of a framework that are not subjected to porcelain veneering and zirconia implants and abutments that are exposed to the oral environment. Non-veneered zirconia frameworks should be avoided and during framework design it is advisable to ensure appropriate space for coating all zirconia surfaces by a thin porcelain or glass layer. Recently reported degradation-free innovative bioceramics such as zirconia magnesia (Mg-PSZ with bioactive glass coating)[213] and alumina composites (ie, 80% TZP of 90 mol% ZrO_2 + 6 mol% Y_2O_3 + 4 mol% Nb_2O_5 composition, and 20% Al_2O_3[217] or 70% TZP stabilized with 10 mol% CeO_2 + 30vol% Al_2O_3 + 0.05 mol% TiO_2)[218] might be a future solution to LTD aging phenomena.[219]

Studies regarding these materials are limited and, particularly for the Ce-TZP/Al_2O_3 nanocomposite of special interest for dentistry, are contradictory. Although both materials exhibit similar activation energies (90 kJ/mol), in comparison to Y-TZP, the Ce-TZP/Al_2O_3 nanocomposite presents a significantly slower transformation from the tetragonal to the monoclinic phase, which is controlled by the chemical reaction of water and the Zr-O-Zr bond.[210] The instability of the tetragonal phase possibly occurs because of the reaction of Y_2O_3 with the aqueous environment (vapor) producing yttrium hydroxide (Y[OH]$_3$H$_2$O).[220] Consequently, along with a satisfactory durability in terms of LTD aging, Ce-TZP/Al_2O_3 may produce a higher biaxial flexure strength than Y-TZP, which is further increased after sandblasting.[211,221] However, apart from improved biomechanical performance, bond strength of Ce-TZP/Al_2O_3 to veneering ceramics is low, and results in a high susceptibility for delamination and chipping.[222]

The technical complications of FPDs identified by most clinical studies with a minimum three-year observation time were predominantly the identification of fractures within the veneering ceramic (chipping) and secondly, fractures of the core and debonding of the restoration. Current clinical studies revealed an increased chipping rate that ranged from 6% to 15% between three to five years (Table 2), while for the metal-ceramic restorations the incidence of chipping was between 4% and 10% after 10 years.[223] Fracture of the zirconia frameworks is highly possible but not probable, and failures can be attributed mainly to biological and technical reasons. However, after appropriate design and material selection, lifetime predictions for posterior Y-TZP FPDs are estimated to be more than 20 years.[224] According to the available data, Y-TZP FPDs can be comparable to the metal-ceramic FPDs and therefore successfully withstand physiologically functional loading forces.[82]

Chipping origin is still unknown and hypothetically could be associated with the bond failure between the veneering material and the zirconia framework.[62] Bond strength at the specific core/veneer interface is mainly dependent on pre-stresses, due to differences in thermal expansion coefficients,[225] poor core wetting and application of liner materials;,[226] porcelain firing shrinkage,[227,228] phase transformation due to thermal influences,[229] loading stresses, inherent flaw formation during processing,[16] and addition of coloring pigments.[230]

Thermal expansion coefficients of the veneering porcelains, especially for zirconia ceramics (8.8 to 10.0 x 10^{-6} per C), have a slight but compatible mismatch to those of zirconia (10.0 to 10.5 x 10^{-6} per C).[231] Since simple thermal expansion coefficient mismatch between bulk materials is not likely to induce tensile stresses that lead to porcelain chipping, it was presupposed that surface property changes may be involved.[213] Moreover, interfacial SEM analysis of the elemental composition and distribution failed to give an explanation of chemical bond since no transitional zone and/or distinct ionic presentations could be detected.[232] Further *in vitro* testing showed that fractures occurred adjacent to the interface but not into the veneering ceramic mass. However, a thin ceramic layer remained on the zirconia surface, indicating that bond strength was higher than the cohesive strength of the veneering ceramic. For this reason, it was assumed that bonding between veneering ceramics and zirconia might be based on chemical bonds.[228] To date, there is no scientific evidence of chemical bonding between zirconia and veneering porcelains. The two materials seem to "bond" by mechanical interlocking and through development of compressive stresses due to thermal shrinkage during cooling after sintering.[211]

Another cause of chipping might be the lack of a uniform support of the veneering ceramic due to the framework design.[28,233] The ceramic framework design is dependent mainly on the preparation depth, height of the abutment teeth, interdental space, and edentulous span length. Regarding all-ceramic FPDs, the shape of the pontic-connector interface seems to have an effect on fracture characteristics, stress distribution, and concentration inside a framework that may induce cracking of the veneering material.[234] Framework designs for posterior implant restorations that curved in the occlusal direction may better withstand functional loading, however, framework design had no significant influence on initial fracture of veneering ceramic.[235] In order to develop a framework that meets all the requirements of physiology, esthetics, and strength, current CAD-CAM systems provide sophisticated features to detect preparation margins, to direct positioning of connectors and pontics and to allow essential planning of both form and support. Most manufactures suggest that the minimum coping thickness should be 0.4 mm, that the minimum connector size should be 9.0 mm^2, and that the framework must support the veneering porcelain, which should not include more than 2.0 mm of unsupported veneering material.[223,234,236]

Chipping or core fractures might furthermore be the result of differences in the modulus of elasticity within the tooth or implant abutment–cement framework and veneering material complex. Elastic property differences across these interfaces can lead to high interfacial stresses and ultimate failure.[66] In general, the use of tougher core materials, such as zirconia, has been advocated to overcome this limitation and therefore improve clinical performance.[237] Zirconia cores were found to be less susceptible to fracture than alumina and critical loads for veneering fracture were not significant, however, veneering fractures did depend on adhesive thickness.[238] For this reason, a standardized thickness of cement space should be used throughout clinical (ie, appropriate tooth preparation)[239] and laboratory procedures (ie, computer-aided cement space determination).[33] Observed fractures of multi-unit prostheses (≥ 4) mostly involve the connectors or second molar abutments. In addition, molar zirconia crowns were found to be at least as good as alumina-based ones.[4]

Finally, the cost-effectiveness of CAD/CAM zirconia applications is an issue open for discussion, because of the need for initial hardware investments (ie, scanners, computers, machines) and because of the increased final per unit cost. After zirconia technology enters routine clinical practice, dentists and dental technicians should cooperatively adopt new materials and methods to improve their performance according to current evidence-based data and manufacturers´ recommendations. Since zirconia technology is a relatively new area of dentistry, it might undergo evolutionary changes in the near future and consequently users and technical staff should also maintain significant continuing education and training.

At the conclusion of the present review, it is essential to underscore that zirconia technology is the most recent of the amazing advances in the CAD/CAM industry. Supporting technologies regarding digitalization, computers, and lasers will continue to revolutionize dentistry so that “virtual labs” might even replace traditional dental technology. Current clinical findings may provide a glimpse of research orientation and highlight future trends. Zirconia already has a past and an ambitious present however, for the fulfillment of the “dream,” all observed or future complications must be overcome through basic research and long-term clinical evaluation.

Conclusions

- Zirconia applications seem to consolidate a well-established position in clinical dentistry, due to the improvements in CAD/CAM technology and to the material’s exceptional physical properties.
- Existing clinical studies demonstrated a promising survival potential regarding tooth-supported restorations but also revealed significant complications such as high incidence of early fractures of either the veneering or the core materials. Longitudinal studies will help to determine the degree of clinical benefit or severity of complications.
- Zirconia abutments provide a favorable bio-esthetic addition to implant dentistry, however, long-term clinical assessment is needed for in-depth evaluation of implant-supported zirconia restorations and zirconia implants in particular.
- Basic research should be conducted in the fields of aging, veneering, framework design, bonding, surface modification and esthetic performance to further illuminate the observed complications and provide solutions that will accelerate expected clinical outcomes.

References

1. Piconi C, Maccauro G. Zirconia as a ceramic biomaterial. Biomaterials 1999;20:1-25.
2. Kelly JR, Denry I. Stabilized zirconia as a structural ceramic: an overview. Dent Mater 2008;24:289-298.
3. Vagkopoulou T, Koutayas SO, Koidis P, Strub JR. Zirconia in Dentistry. Part 1: Discovering the nature of an upcoming bioceramic. Eur J Esthet Dent 2009;4:130-151.
4. Denry I, Kelly JR. State of the art of zirconia for dental applications. Dent Mater 2008;24:299-307.
5. Manicone PF, Rossi Iommetti P, Raffaelli L. An overview of zirconia ceramics: basic properties and clinical applications. J Dent 2007;35:819-826.
6. Chevalier J. What future for zirconia as a biomaterial? Biomaterials 2006;27:535-543.
7. Griffin J. The Origin of Dreams: How and why we evolved to dream, vol 4. Worthing: The Therapist Ltd, 1997.
8. Kohal RJ, Klaus G, Strub JR. Zirconia-implant-supported all-ceramic crowns withstand long-term load: a pilot investigation. Clin Oral Implants Res 2006;17:565-571.
9. Tinschert J, Natt G, Hassenpflug S, Spiekermann H. Status of current CAD/CAM technology in dental medicine. Int J Comput Dent 2004;7:25-45.
10. Witkowski S. CAD-CAM in dental technology. Quintessence J Dent Technol 2005;28:1-16.
11. Oetzel C, Clasen R. Preparation of zirconia dental crowns via electrophoretic deposition. J Mater Sci 2006;41:8130-8137.

12. Filser F, Kocher P, Weibel F, Luthy H, Scharer P, Gauckler LJ. Reliability and strength of all-ceramic dental restorations fabricated by direct ceramic machining (DCM). Int J Comput Dent 2001;4:89-106.
13. Raigrodski AJ. Clinical and laboratory considerations for the use of CAD/CAM Y-TZP-based restorations. Pract Proced Aesthet Dent 2003;15:469-476.
14. Tinschert J, Zwez D, Marx R, Anusavice KJ. Structural reliability of alumina-, feldspar-, leucite-, mica- and zirconia-based ceramics. J Dent 2000;28:529-535.
15. Luthardt RG, Holzhuter MS, Rudolph H, Herold V, Walter MH. CAD/CAM-machining effects on Y-TZP zirconia. Dent Mater 2004;20:655-662.
16. Wang H, Aboushelib MN, Feilzer AJ. Strength influencing variables on CAD/CAM zirconia frameworks. Dent Mater 2008;24:633-638.
17. Rekow D, Thompson VP. Near-surface damage—a persistent problem in crowns obtained by computer-aided design and manufacturing. Proc Inst Mech Eng [H] 2005;219:233-243.
18. Gurel G. The science and art of porcelain laminate veneers. London: Quintessence Publishing Co Ltd, 2003.
19. Hager B, Oden A, Andersson B, Andersson L. Procera All-Ceram laminates: a clinical report. J Prosthet Dent 2001;85:231-232.
20. Miyasaki M. Aesthetic rehabilitation of the severely discolored anterior dentition: restorative considerations using all-ceramic veneers. Pract Proced Aesthet Dent 2004;16:277-281.
21. Chu FC, Andersson B, Deng FL, Chow TW. Making porcelain veneers with the Procera AllCeram system: case studies. Dent Update 2003;30:454-458,460.
22. Okamura M, Chen KK, Kakigawa H, Kozono Y. Application of alumina coping to porcelain laminate veneered crown: part 1 masking ability for discolored teeth. Dent Mater J 2004;23:180-183.
23. Zhang F, Heydecke G, Razzoog ME. Double-layer porcelain veneers: effect of layering on resulting veneer color. J Prosthet Dent 2000;84:425-431.
24. Charisis D, Koutayas SO, Kamposiora P, Doukoudakis A. Spectrophotometric evaluation of the influence of different backgrounds on the color of glass-infiltrated ceramic veneers. Eur J Esthet Dent 2006;1:142-156.
25. Koutayas SO, Charisis D. Influence of the core material and the glass infiltration mode on the color of glass-infiltrated ceramic veneers over discolored backgrounds. A spectrophotometric evaluation. Eur J Esthet Dent 2008;2:160-173.
26. Heffernan MJ, Aquilino SA, Diaz-Arnold AM, Haselton DR, Stanford CM, Vargas MA. Relative translucency of six all-ceramic systems. Part I: core materials. J Prosthet Dent 2002;88:4-9.
27. Heffernan MJ, Aquilino SA, Diaz-Arnold AM, Haselton DR, Stanford CM, Vargas MA. Relative translucency of six all-ceramic systems. Part II: core and veneer materials. J Prosthet Dent 2002;88:10-15.
28. Donovan TE. Factors essential for successful all-ceramic restorations. J Am Dent Assoc 2008;139(Suppl):14S-18S.
29. Sadan A, Blatz MB, Lang B. Clinical considerations for densely sintered alumina and zirconia restorations: Part 1. Int J Periodontics Restorative Dent 2005;25:213-219.
30. Beuer F, Aggstaller H, Edelhoff D, Gernet W. Effect of preparation design on the fracture resistance of zirconia crown copings. Dent Mater J 2008;27:362-367.
31. Reich S, Petschelt A, Lohbauer U. The effect of finish line preparation and layer thickness on the failure load and fractography of ZrO_2 copings. J Prosthet Dent 2008;99:369-376.
32. De Jager N, Pallav P, Feilzer AJ. The influence of design parameters on the FEA-determined stress distribution in CAD-CAM produced all-ceramic dental crowns. Dent Mater 2005;21:242-251.
33. Iwai T, Komine F, Kobayashi K, Saito A, Matsumura H. Influence of convergence angle and cement space on adaptation of zirconium dioxide ceramic copings. Acta Odontol Scand 2008;66:214-218.
34. Ernst CP, Cohnen U, Stender E, Willershausen B. *In vitro* retentive strength of zirconium oxide ceramic crowns using different luting agents. J Prosthet Dent 2005;93:551-558.
35. Palacios RP, Johnson GH, Phillips KM, Raigrodski AJ. Retention of zirconium oxide ceramic crowns with three types of cement. J Prosthet Dent 2006;96:104-114.
36. Blatz MB. Adhesive cementation of high-strength ceramics. J Esthet Restor Dent 2007;19:238-239.
37. Kosmac T, Oblak C, Jevnikar P, Funduk N, Marion L. The effect of surface grinding and sandblasting on flexural strength and reliability of Y-TZP zirconia ceramic. Dent Mater 1999;15:426-433.
38. Wegner SM, Kern M. Long-term resin bond strength to zirconia ceramic. J Adhes Dent 2000;2:139-147.
39. Blatz MB, Chiche G, Holst S, Sadan A. Influence of surface treatment and simulated aging on bond strengths of luting agents to zirconia. Quintessence Int 2007;38:745-753.

40. Tsukakoshi M, Shinya A, Gomi H, Lassila LV, Vallittu PK. Effects of dental adhesive cement and surface treatment on bond strength and leakage of zirconium oxide ceramics. Dent Mater J 2008;27:159-171.
41. Kern M, Wegner SM. Bonding to zirconia ceramic: adhesion methods and their durability. Dent Mater 1998;14:64-71.
42. Blatz MB, Sadan A, Kern M. Resin-ceramic bonding: a review of the literature. J Prosthet Dent 2003;89:268-274.
43. Wolfart M, Lehmann F, Wolfart S, Kern M. Durability of the resin bond strength to zirconia ceramic after using different surface conditioning methods. Dent Mater 2007;23:45-50.
44. Atsu SS, Kilicarslan MA, Kucukesmen HC, Aka PS. Effect of zirconium-oxide ceramic surface treatments on the bond strength to adhesive resin. J Prosthet Dent 2006;95:430-436.
45. Xible AA, de Jesus Tavarez RR, de Araujo Cdos R, Bonachela WC. Effect of silica coating and silanization on flexural and composite-resin bond strengths of zirconia posts: An *in vitro* study. J Prosthet Dent 2006;95:224-229.
46. Derand P, Derand T. Bond strength of luting cements to zirconium oxide ceramics. Int J Prosthodont 2000;13:131-135.
47. Derand T, Molin M, Kvam K. Bond strength of composite luting cement to zirconia ceramic surfaces. Dent Mater 2005;21:1158-1162.
48. Wegner SM, Gerdes W, Kern M. Effect of different artificial aging conditions on ceramic-composite bond strength. Int J Prosthodont 2002;15:267-272.
49. Yang B, Scharnberg M, Wolfart S, Quaas AC, Ludwig K, Adelung R, et al. Influence of contamination on bonding to zirconia ceramic. J Biomed Mater Res B Appl Biomater 2007;81:283-290.
50. Quaas AC, Yang B, Kern M. Panavia F 2.0 bonding to contaminated zirconia ceramic after different cleaning procedures. Dent Mater 2007;23:506-512.
51. Carracho JF, Razzoog ME. Removable partial denture abutments restored with all-ceramic surveyed crowns. Quintessence Int 2006;37:283-288.
52. Pellecchia R, Kang KH, Hirayama H. Fixed partial denture supported by all-ceramic copings: a clinical report. J Prosthet Dent 2004;92:220-223.
53. Rosch R, Mericske-Stern R. [Zirconia and removable partial dentures]. Schweiz Monatsschr Zahnmed 2008;118:959-974.
54. Raigrodski AJ. Contemporary all-ceramic fixed partial dentures: a review. Dent Clin North Am 2004;48:531-544.
55. White SN, Miklus VG, McLaren EA, Lang LA, Caputo AA. Flexural strength of a layered zirconia and porcelain dental all-ceramic system. J Prosthet Dent 2005;94:125-131.
56. Studart AR, Filser F, Kocher P, Gauckler LJ. Fatigue of zirconia under cyclic loading in water and its implications for the design of dental bridges. Dent Mater 2007;23:106-114.
57. Fritzsche J. Zirconium oxide restorations with the DCS precident system. Int J Comput Dent 2003;6:193-201.
58. Burke FJ, Ali A, Palin WM. Zirconia-based all-ceramic crowns and bridges: three case reports. Dent Update 2006;33:401,402,405,406,409,410.
59. Keough BE, Kay HB, Sager RD. A ten-unit all-ceramic anterior fixed partial denture using Y-TZP zirconia. Pract Proced Aesthet Dent 2006;18:37-43.
60. Luthy H, Filser F, Loeffel O, Schumacher M, Gauckler LJ, Hammerle CH. Strength and reliability of four-unit all-ceramic posterior bridges. Dent Mater 2005;21:930-937.
61. Tinschert J, Natt G, Mautsch W, Augthun M, Spiekermann H. Fracture resistance of lithium disilicate-, alumina-, and zirconia-based three-unit fixed partial dentures: a laboratory study. Int J Prosthodont 2001;14:231-238.
62. Studart AR, Filser F, Kocher P, Luthy H, Gauckler LJ. Mechanical and fracture behavior of veneer-framework composites for all-ceramic dental bridges. Dent Mater 2007;23:115-123.
63. Kamposiora P, Papavasiliou G, Bayne SC, Felton DA. Stress concentration in all-ceramic posterior fixed partial dentures. Quintessence Int 1996;27:701-706.
64. Fischer H, Weber M, Marx R. Lifetime prediction of all-ceramic bridges by computational methods. J Dent Res 2003;82:238-242.
65. Oh WS, Anusavice KJ. Effect of connector design on the fracture resistance of all-ceramic fixed partial dentures. J Prosthet Dent 2002;87:536-542.
66. Kelly JR, Tesk JA, Sorensen JA. Failure of all-ceramic fixed partial dentures *in vitro* and *in vivo*: analysis and modeling. J Dent Res 1995;74:1253-1258.
67. Proos K, Steven G, Swain M, Ironside J. Preliminary studies on the optimum shape of dental bridges. Comput Methods Biomech Biomed Engin 2000;4:77-92.

68. White SN, Caputo AA, Vidjak FM, Seghi RR. Moduli of rupture of layered dental ceramics. Dent Mater 1994;10:52-58.
69. Zeng K, Oden A, Rowcliffe D. Evaluation of mechanical properties of dental ceramic core materials in combination with porcelains. Int J Prosthodont 1998;11:183-189.
70. Guazzato M, Proos K, Quach L, Swain MV. Strength, reliability and mode of fracture of bilayered porcelain/zirconia (Y-TZP) dental ceramics. Biomaterials 2004;25:5045-5052.
71. Vult von Steyern P, Carlson P, Nilner K. All-ceramic fixed partial dentures designed according to the DC-Zirkon technique. A 2-year clinical study. J Oral Rehabil 2005;32:180-187.
72. Att W, Grigoriadou M, Strub JR. ZrO_2 three-unit fixed partial dentures: comparison of failure load before and after exposure to a mastication simulator. J Oral Rehabil 2007;34:282-290.
73. Att W, Stamouli K, Gerds T, Strub JR. Fracture resistance of different zirconium dioxide three-unit all-ceramic fixed partial dentures. Acta Odontol Scand 2007;65:14-21.
74. Larsson C, Holm L, Lovgren N, Kokubo Y, Vult von Steyern P. Fracture strength of four-unit Y-TZP FPD cores designed with varying connector diameter. An *in-vitro* study. J Oral Rehabil 2007;34:702-709.
75. Reich S, Wichmann M, Nkenke E, Proeschel P. Clinical fit of all-ceramic three-unit fixed partial dentures, generated with three different CAD/CAM systems. Eur J Oral Sci 2005;113:174-179.
76. Komine F, Gerds T, Witkowski S, Strub JR. Influence of framework configuration on the marginal adaptation of zirconium dioxide ceramic anterior four-unit frameworks. Acta Odontol Scand 2005;63:361-366.
77. Costello RV, Thompson J, Sadan A, Burgess JO, Blatz MB. Light transmission of high-strength ceramics with four curing lights. J Dent Res 2004;83(special issue A):IADR Abstract No.1813.
78. Zhang Y, Lawn BR, Rekow ED, Thompson VP. Effect of sandblasting on the long-term performance of dental ceramics. J Biomed Mater Res B Appl Biomater 2004;71:381-386.
79. Sundh A, Molin M, Sjogren G. Fracture resistance of yttrium oxide partially-stabilized zirconia all-ceramic bridges after veneering and mechanical fatigue testing. Dent Mater 2005;21:476-482.
80. Guazzato M, Quach L, Albakry M, Swain MV. Influence of surface and heat treatments on the flexural strength of Y-TZP dental ceramic. J Dent 2005;33:9-18.
81. Sundh A, Sjogren G. Fracture resistance of all-ceramic zirconia bridges with differing phase stabilizers and quality of sintering. Dent Mater 2006;22:778-784.
82. Sailer I, Feher A, Filser F, Gauckler LJ, Luthy H, Hammerle CH. Five-year clinical results of zirconia frameworks for posterior fixed partial dentures. Int J Prosthodont 2007;20:383-388.
83. Sturzenegger B, Feher A, Luthy H, Schumacher M, Loeffel O, Filser F, et al. [Clinical study of zirconium oxide bridges in the posterior segments fabricated with the DCM system]. Schweiz Monatsschr Zahnmed 2000; 110:131-139.
84. Tinschert J, Schulze KA, Natt G, Latzke P, Heussen N, Spiekermann H. Clinical behavior of zirconia-based fixed partial dentures made of DC-Zirkon: 3-year results. Int J Prosthodont 2008;21:217-222.
85. Molin MK, Karlsson SL. Five-year clinical prospective evaluation of zirconia-based Denzir 3-unit FPDs. Int J Prosthodont 2008;21:223-227.
86. Sailer I, Feher A, Filser F, Luthy H, Gauckler LJ, Scharer P, et al. Prospective clinical study of zirconia posterior fixed partial dentures: 3-year follow-up. Quintessence Int 2006;37:685-693.
87. Raigrodski AJ, Chiche GJ, Potiket N, Hochstedler JL, Mohamed SE, Billiot S, et al. The efficacy of posterior three-unit zirconium-oxide-based ceramic fixed partial dental prostheses: a prospective clinical pilot study. J Prosthet Dent 2006;96:237-244.
88. Pospiech PR, Rountree PR, Nothdurft FP. Clinical evaluation of zirconia-based allceramic posterior bridges: two-year results. J Dent Res 2003; 82(Special Issue B):114,IADR Abstract No.817.
89. Bornemann G, Rinke S, Huels A. Prospective clinical trial with conventionally luted zirconia-based fixed partial dentures - 18-month results. J Dent Res 2003;82(special issue B):117,IADR Abstract No. 842.
90. Edelhoff D, Beuer F, Weber V, Johnen C. HIP zirconia fixed partial dentures. Clinical results after 3 years of clinical service. Quintessence Int 2008;39:459-471.
91. Roediger M, Rinke S, Huels A. Prospective clinical evaluation of Cercon™ premolar and molar FPDs. J Dent Res 2009;88(special issue B):IADR Abstract No. 2347.
92. Taskonak B, Yan J, Mecholsky JJ, Jr., Sertgoz A, Kocak A. Fractographic analyses of zirconia-based fixed partial dentures. Dent Mater 2008;24:1077-1082.

93. Larsson C, Vult von Steyern P, Sunzel B, Nilner K. All-ceramic two- to five-unit implant-supported reconstructions. A randomized, prospective clinical trial. Swed Dent J 2006;30:45-53.
94. Komine F, Tomic M. A single-retainer zirconium dioxide ceramic resin-bonded fixed partial denture for single tooth replacement: a clinical report. J Oral Sci 2005;47:139-142.
95. Hirata R, Viotti R, Reis AF, de Andrade OS. All-ceramic inlay-retained fixed partial bridge using a CAD-CAM produced Y-TZP framework and fluoroapatite veneering ceramic: a clinical report. Gen Dent 2007;55:657-662.
96. Koutayas SO, Kern M, Ferraresso F, Strub JR. Influence of design and mode of loading on the fracture strength of all-ceramic resin-bonded fixed partial dentures: an *in vitro* study in a dual-axis chewing simulator. J Prosthet Dent 2000;83:540-547.
97. Kern M, Strub JR. Bonding to alumina ceramic in restorative dentistry: clinical results over up to 5 years. J Dent 1998;26:245-249.
98. Kern M. Clinical long-term survival of two-retainer and single-retainer all-ceramic resin-bonded fixed partial dentures. Quintessence Int 2005;36:141-147.
99. Kilicarslan MA, Kedici PS, Kucukesmen HC, Uludag BC. *In vitro* fracture resistance of posterior metal-ceramic and all-ceramic inlay-retained resin-bonded fixed partial dentures. J Prosthet Dent 2004;92:365-370.
100. Ohlmann B, Gabbert O, Schmitter M, Gilde H, Rammelsberg P. Fracture resistance of the veneering on inlay-retained zirconia ceramic fixed partial dentures. Acta Odontol Scand 2005;63:335-342.
101. Wolfart S, Ludwig K, Uphaus A, Kern M. Fracture strength of all-ceramic posterior inlay-retained fixed partial dentures. Dent Mater 2007;23:1513-1520.
102. Takeda T, Ishigami K, Shimada A, Ohki K. A study of discoloration of the gingiva by artificial crowns. Int J Prosthodont 1996;9:197-202.
103. Frejlich S, Goodacre CJ. Eliminating coronal discoloration when cementing all-ceramic restorations over metal posts and cores. J Prosthet Dent 1992;67:576-577.
104. Kwiatkowski S, Geller W. A preliminary consideration of the glass-ceramic dowel post and core. Int J Prosthodont 1989;2:51-55.
105. Kern M, Knode H. Posts and cores fabricated out of In-Ceram—direct and indirect methods. Quintessenz Zahntech 1991;17:917-925.
106. Sandhaus S, Pasche K. Tenon radiculaire en zircone pour la réalisation d'inlays-cores tout céramique. Tribune Dent 1994;2:17-24.
107. Meyenberg KH, Luthy H, Scharer P. Zirconia posts: a new all-ceramic concept for nonvital abutment teeth. J Esthet Dent 1995;7:73-80.
108. Simon M, Paffrath J. Neue Perspektiven zur vollkeramischen Stabilisierung und zum Aufbau devitaler Zähne. Quintessenz 1995;46:1085-1101.
109. Ahmad I. Yttrium-partially stabilized zirconium dioxide posts: an approach to restoring coronally compromised nonvital teeth. Int J Periodontics Restorative Dent 1998;18:454-465.
110. Fradeani M, Aquilano A, Barducci G. Aesthetic restoration of endodontically treated teeth. Pract Periodontics Aesthet Dent 1999;11:761-768.
111. Schultze-Mosgau S, Rekersbrink M, Neukam FW. Clinical and roentgenologic outcome evaluation after apicoectomy with zirconium oxide ceramic pins—a prospective study of 112 apicoectomy teeth. Fortschr Kiefer Gesichtschir 1995;40:144-147.
112. Pontius O, Hutter JW. Survival rate and fracture strength of incisors restored with different post and core systems and endodontically treated incisors without coronoradicular reinforcement. J Endod 2002;28:710-715.
113. Heydecke G, Butz F, Strub JR. Fracture strength and survival rate of endodontically treated maxillary incisors with approximal cavities after restoration with different post and core systems: an *in-vitro* study. J Dent 2001;29:427-433.
114. Koutayas SO, Kern M. All-ceramic posts and cores: the state of the art. Quintessence Int 1999;30:383-392.
115. Butz F, Lennon AM, Heydecke G, Strub JR. Survival rate and fracture strength of endodontically treated maxillary incisors with moderate defects restored with different post-and-core systems: an *in vitro* study. Int J Prosthodont 2001;14:58-64.
116. Strub JR, Pontius O, Koutayas S. Survival rate and fracture strength of incisors restored with different post and core systems after exposure in the artificial mouth. J Oral Rehabil 2001;28:120-124.
117. Heydecke G, Peters MC. The restoration of endodontically treated, single-rooted teeth with cast or direct posts and cores: a systematic review. J Prosthet Dent 2002;87:380-386.
118. Friedel W, Kern M. Fracture strength of teeth restored with all-ceramic posts and cores. Quintessence Int 2006;37:289-295.
119. Maccari PC, Conceicao EN, Nunes MF. Fracture resistance of endodontically treated teeth restored with three different prefabricated esthetic posts. J Esthet Restor Dent 2003;15:25-30.

120. Hu YH, Pang LC, Hsu CC, Lau YH. Fracture resistance of endodontically treated anterior teeth restored with four post-and-core systems. Quintessence Int 2003;34:349-353.
121. Kakehashi Y, Luthy H, Naef R, Wohlwend A, Scharer P. A new all-ceramic post and core system: clinical, technical, and *in vitro* results. Int J Periodontics Restorative Dent 1998;18:586-593.
122. Schneider U. Die Versorgung avitaler Zähne mit Wurzelstiften aus Zirkondioxidkeramik - Eine Langzeitstudie beim Menschen [thesis]. University of Freiburg, Germany, 1999.
123. Paul SJ, Werder P. Clinical success of zirconium oxide posts with resin composite or glass-ceramic cores in endodontically treated teeth: a 4-year retrospective study. Int J Prosthodont 2004;17:524-528.
124. Schmitter M, Mussotter K, Ohlmann B, Gilde H, Rammelsberg P. Dependence of *in vitro* fracture strength of adhesive core buildup and crown complexes on preparation design and cementation technique. J Adhes Dent 2008;10:145-150.
125. Caputo AA, Standlee JP. Restoration of endodontically involved teeth. In: Biomechanics in clinical dentistry. Chicago: Quintessence; 1987:185-203.
126. Akkayan B, Gulmez T. Resistance to fracture of endodontically treated teeth restored with different post systems. J Prosthet Dent 2002;87:431-437.
127. Dietschi D, Ardu S, Rossier-Gerber A, Krejci I. Adaptation of adhesive post and cores to dentin after *in vitro* occlusal loading: evaluation of post material influence. J Adhes Dent 2006;8:409-419.
128. Dietschi D, Duc O, Krejci I, Sadan A. Biomechanical considerations for the restoration of endodontically treated teeth: a systematic review of the literature—Part 1. Composition and micro- and macrostructure alterations. Quintessence Int 2007;38:733-743.
129. Dietschi D, Duc O, Krejci I, Sadan A. Biomechanical considerations for the restoration of endodontically treated teeth: a systematic review of the literature, Part II (Evaluation of fatigue behavior, interfaces, and *in vivo* studies). Quintessence Int 2008;39:117-129.
130. Weingart D, Steinemann S, Schilli W, Strub JR, Hellerich U, Assenmacher J, et al. Titanium deposition in regional lymph nodes after insertion of titanium screw implants in maxillofacial region. Int J Oral Maxillofac Surg 1994;23:450-452.
131. Bianco PD, Ducheyne P, Cuckler JM. Systemic titanium levels in rabbits with a titanium implant in the absence of wear. J Mater Sci Mater Med 1997;8:525-529.
132. Lalor PA, Revell PA, Gray AB, Wright S, Railton GT, Freeman MA. Sensitivity to titanium. A cause of implant failure? J Bone Joint Surg Br 1991;73:25-28.
133. Tschernitschek H, Borchers L, Geurtsen W. Nonalloyed titanium as a bioinert metal—a review. Quintessence Int 2005;36:523-530.
134. Kawahara H, Hirabayashi M, Shikita T. Single crystal alumina for dental implants and bone screws. J Biomed Mater Res 1980;14:597-605.
135. Schepers E, De Clercq M, Ducheyne P. Fiber-reinforced bioactive glass: a possible dental implant material. Biomed Tech (Berl) 1987;32:309-312.
136. Simunek A, Kopecka D, Cierny M, Krulichova I. A six-year study of hydroxyapatite-coated root-form dental implants. West Indian Med J 2005;54:393-397.
137. Volz U, Blaschke C. Metal-free reconstruction with zirconia implants and zirconia crowns. Quintessence J Dent Technol 2004;2:324-330.
138. Kohal RJ, Klaus G. A zirconia implant-crown system: a case report. Int J Periodontics Restorative Dent 2004;24:147-153.
139. Polack MA. Restoration of maxillary incisors with a zirconia all-ceramic system: a case report. Quintessence Int 2006;37:375-380.
140. Filiaggi MJ, Pilliar RM, Yakubovich R, Shapiro G. Evaluating sol-gel ceramic thin films for metal implant applications. I. Processing and structure of zirconia films on Ti-6Al-4V. J Biomed Mater Res 1996;33:225-238.
141. Sollazzo V, Pezzetti F, Scarano A, Piattelli A, Bignozzi CA, Massari L, et al. Zirconium oxide coating improves implant osseointegration *in vivo*. Dent Mater 2008;24:357-361.
142. Heuer D, Harrison A, Gupta H, Hunter G. Chemically textured and oxidized zirconium surfaces for implant fixation. Key Eng Mater 2003;240-242:789-792.
143. Soares CJ, Mitsui FH, Neto FH, Marchi GM, Martins LR. Radiodensity evaluation of seven root post systems. Am J Dent 2005;18:57-60.
144. Park SW, Driscoll CF, Romberg EE, Siegel S, Thompson G. Ceramic implant abutments: Cutting efficiency and resultant surface finish by diamond rotary cutting instruments. J Prosthet Dent 2006;95:444-449.
145. Ichikawa Y, Akagawa Y, Nikai H, Tsuru H. Tissue compatibility and stability of a new zirconia ceramic *in vivo*. J Prosthet Dent 1992;68:322-326.
146. Hayashi K, Inadome T, Tsumura H, Mashima T, Sugioka Y. Bone-implant interface mechanics of *in vivo* bio-inert ceramics. Biomaterials 1993;14:1173-1179.

147. Kohal RJ, Att W, Bachle M, Butz F. Ceramic abutments and ceramic oral implants. An update. Periodontol 2000 2008;47:224-243.
148. Josset Y, Oum'Hamed Z, Zarrinpour A, Lorenzato M, Adnet JJ, Laurent-Maquin D. *In vitro* reactions of human osteoblasts in culture with zirconia and alumina ceramics. J Biomed Mater Res 1999;47:481-493.
149. Bachle M, Butz F, Hubner U, Bakalinis E, Kohal RJ. Behavior of CAL72 osteoblast-like cells cultured on zirconia ceramics with different surface topographies. Clin Oral Implants Res 2007;18:53-59.
150. Hao L, Lawrence J, Chian KS. Effects of CO_2 laser irradiation on the surface properties of magnesia-partially stabilised zirconia (MgO-PSZ) bioceramic and the subsequent improvements in human osteoblast cell adhesion. J Biomater Appl 2004;19:81-105.
151. Hao L, Lawrence J, Chian KS. Osteoblast cell adhesion on a laser modified zirconia based bioceramic. J Mater Sci Mater Med 2005;16:719-726.
152. Carinci F, Pezzetti F, Volinia S, Francioso F, Arcelli D, Farina E, et al. Zirconium oxide: analysis of MG63 osteoblast-like cell response by means of a microarray technology. Biomaterials 2004;25:215-228.
153. Sollazzo V, Palmieri A, Pezzetti F, Bignozzi CA, Argazzi R, Massari L et al. Genetic effect of zirconium oxide coating on osteoblast-like cells. J Biomed Mater Res B Appl Biomater 2008;84:550-558.
154. Palmieri A, Pezzetti F, Brunelli G, Zollino I, Lo Muzio L, Martinelli M et al. Zirconium oxide regulates RNA interfering of osteoblast-like cells. J Mater Sci Mater Med 2008;19:2471-2476.
155. Dubruille JH, Viguier E, Le Naour G, Dubruille MT, Auriol M, Le Charpentier Y. Evaluation of combinations of titanium, zirconia, and alumina implants with 2 bone fillers in the dog. Int J Oral Maxillofac Implants 1999;14:271-277.
156. Schultze-Mosgau S, Schliephake H, Radespiel-Troger M, Neukam FW. Osseointegration of endodontic endosseous cones: zirconium oxide vs titanium. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 2000;89:91-98.
157. Scarano A, Di Carlo F, Quaranta M, Piattelli A. Bone response to zirconia ceramic implants: an experimental study in rabbits. J Oral Implantol 2003;29:8-12.
158. Sennerby L, Dasmah A, Larsson B, Iverhed M. Bone tissue responses to surface-modified zirconia implants: A histomorphometric and removal torque study in the rabbit. Clin Implant Dent Relat Res 2005;7(suppl 1):S13-S20.
159. Gahlert M, Gudehus T, Eichhorn S, Steinhauser E, Kniha H, Erhardt W. Biomechanical and histomorphometric comparison between zirconia implants with varying surface textures and a titanium implant in the maxilla of miniature pigs. Clin Oral Implants Res 2007;18:662-668.
160. Akagawa Y, Ichikawa Y, Nikai H, Tsuru H. Interface histology of unloaded and early loaded partially stabilized zirconia endosseous implant in initial bone healing. J Prosthet Dent 1993;69:599-604.
161. Kohal RJ, Papavasiliou G, Kamposiora P, Tripodakis A, Strub JR. Three-dimensional computerized stress analysis of commercially pure titanium and yttrium-partially stabilized zirconia implants. Int J Prosthodont 2002;15:189-194.
162. Kohal RJ, Finke HC, Klaus G. Stability of prototype two-piece zirconia and titanium implants after artificial aging: an *in vitro* pilot study. Clin Implant Dent Relat Res 2008;[Epub ahead of print].
163. Andreiotelli M, Kohal RJ. Fracture strength of zirconia implants after artificial aging. Clin Implant Dent Relat Res 2008;[Epub ahead of print].
164. Pirker W, Kocher A. Immediate, non-submerged, root-analogue zirconia implant in single tooth replacement. Int J Oral Maxillofac Surg 2008;37:293-295.
165. Mellinghoff J. First clinical results of dental screw implants made of zirconium oxide. Zahnärztl Impl 2006;22:288-293.
166. Oliva J, Oliva X, Oliva JD. One-year follow-up of first consecutive 100 zirconia dental implants in humans: a comparison of 2 different rough surfaces. Int J Oral Maxillofac Implants 2007;22:430-435.
167. Wenz HJ, Bartsch J, Wolfart S, Kern M. Osseointegration and clinical success of zirconia dental implants: a systematic review. Int J Prosthodont 2008; 21:27-36.
168. Jung RE, Pjetursson BE, Glauser R, Zembic A, Zwahlen M, Lang NP. A systematic review of the 5-year survival and complication rates of implant-supported single crowns. Clin Oral Implants Res 2008;19:119-130.
169. Watkin A, Kerstein RB. Improving darkened anterior peri-implant tissue color with zirconia custom implant abutments. Compend Contin Educ Dent 2008;29:238-240,242.
170. Hurzeler MB, Quinones CR, Strub JR. Advanced surgical and prosthetic management of the anterior single tooth osseointegrated implant: a case presentation. Pract Periodontics Aesthet Dent 1994;6:13-21.

171. Belser UC, Schmid B, Higginbottom F, Buser D. Outcome analysis of implant restorations located in the anterior maxilla: a review of the recent literature. Int J Oral Maxillofac Implants 2004;19(suppl):30-42.
172. Holst S, Blatz MB, Hegenbarth E, Wichmann M, Eitner S. Prosthodontic considerations for predictable single-implant esthetics in the anterior maxilla. J Oral Maxillofac Surg 2005;63:89-96.
173. Yildirim M, Edelhoff D, Hanisch O, Spiekermann H. Ceramic abutments—a new era in achieving optimal esthetics in implant dentistry. Int J Periodontics Restorative Dent 2000;20:81-91.
174. Prestipino V, Ingber A. Esthetic high-strength implant abutments. Part I. J Esthet Dent 1993;5:29-36.
175. Prestipino V, Ingber A. Esthetic high-strength implant abutments. Part II. J Esthet Dent 1993;5:63-68.
176. Andersson B. Implants for single-tooth replacement. A clinical and experimental study on the Brånemark CeraOne System. Swed Dent J Suppl 1995;108:1-41.
177. Prestipino V, Ingber A. All-ceramic implant abutments: esthetic indications. J Esthet Dent 1996;8:255-262.
178. Butz F, Heydecke G, Okutan M, Strub JR. Survival rate, fracture strength and failure mode of ceramic implant abutments after chewing simulation. J Oral Rehabil 2005;32:838-843.
179. Andersson B, Glauser R, Maglione M, Taylor A. Ceramic implant abutments for short-span FPDs: a prospective 5-year multicenter study. Int J Prosthodont 2003;16:640-646.
180. Manicone PF, Rossi Iommetti P, Raffaelli L, Paolantonio M, Rossi G, Berardi D, Perfetti G. Biological considerations on the use of zirconia for dental devices. Int J Immunopathol Pharmacol 2007;20:9-12.
181. Scarano A, Piattelli M, Caputi S, Favero GA, Piattelli A. Bacterial adhesion on commercially pure titanium and zirconium oxide disks: an *in vivo* human study. J Periodontol 2004;75:292-296.
182. Rimondini L, Cerroni L, Carrassi A, Torricelli P. Bacterial colonization of zirconia ceramic surfaces: an *in vitro* and *in vivo* study. Int J Oral Maxillofac Implants 2002;17:793-798.
183. Warashina H, Sakano S, Kitamura S, Yamauchi KI, Yamaguchi J, Ishiguro N, Hasegawa Y. Biological reaction to alumina, zirconia, titanium and polyethylene particles implanted onto murine calvaria. Biomaterials 2003;24:3655-3661.
184. Welander M, Abrahamsson I, Berglundh T. The mucosal barrier at implant abutments of different materials. Clin Oral Implants Res 2008;19:635-641.
185. Glauser R, Sailer I, Wohlwend A, Studer S, Schibli M, Schärer P. Experimental zirconia abutments for implant-supported single-tooth restorations in esthetically demanding regions: 4-year results of a prospective clinical study. Int J Prosthodont 2004;17:285-290.
186. Bae KH, Han JS, Seol YJ, Butz F, Caton J, Rhyu IC. The biologic stability of alumina-zirconia implant abutments after 1 year of clinical service: a digital subtraction radiographic evaluation. Int J Periodontics Restorative Dent 2008;28:137-143.
187. Degidi M, Artese L, Scarano A, Perrotti V, Gehrke P, Piattelli A. Inflammatory infiltrate, microvessel density, nitric oxide synthase expression, vascular endothelial growth factor expression, and proliferative activity in peri-implant soft tissues around titanium and zirconium oxide healing caps. J Periodontol 2006;77:73-80.
188. Linkevicius T, Apse P. Influence of abutment material on stability of peri-implant tissues: a systematic review. Int J Oral Maxillofac Implants 2008;23:449-456.
189. Mustafa K, Wennerberg A, Arvidson K, Messelt EB, Haag P, Karlsson S. Influence of modifying and veneering the surface of ceramic abutments on cellular attachment and proliferation. Clin Oral Implants Res 2008;19:1178-1187.
190. Mitsias M, Koutayas SO, Wolfart S, Lehmann F, Kern M. Fracture strength of implant crowns after different zirconia abutment preparations. IADR 86th General Session & Exhibition, Toronto, 2008; IADR Abstact No. 1211.
191. Brodbeck U. The ZiReal Post: A new ceramic implant abutment. J Esthet Restor Dent 2003;15:10-23,discussion 24.
192. Lang LA, Sierraalta M, Hoffensperger M, Wang RF. Evaluation of the precision of fit between the Procera custom abutment and various implant systems. Int J Oral Maxillofac Implants 2003;18:652-658.
193. Vigolo P, Fonzi F, Majzoub Z, Cordioli G. An *in vitro* evaluation of titanium, zirconia, and alumina procera abutments with hexagonal connection. Int J Oral Maxillofac Implants 2006;21:575-580.
194. Tripodakis AP, Strub JR, Kappert HF, Witkowski S. Strength and mode of failure of single implant all-ceramic abutment restorations under static load. Int J Prosthodont 1995;8:265-272.
195. Papavasiliou G, Tripodakis AP, Kamposiora P, Strub JR, Bayne SC. Finite element analysis of ceramic abutment-restoration combinations for osseointegrated implants. Int J Prosthodont 1996;9:254-260.

196. Vigolo P, Fonzi F, Majzoub Z, Cordioli G. An *in vitro* evaluation of ZiReal abutments with hexagonal connection: in original state and following abutment preparation. Int J Oral Maxillofac Implants 2005;20:108-114.
197. Yildirim M, Fischer H, Marx R, Edelhoff D. *In vivo* fracture resistance of implant-supported all-ceramic restorations. J Prosthet Dent 2003;90:325-331.
198. Att W, Kurun S, Gerds T, Strub JR. Fracture resistance of single-tooth implant-supported all-ceramic restorations after exposure to the artificial mouth. J Oral Rehabil 2006;33:380-386.
199. Gehrke P, Dhom G, Brunner J, Wolf D, Degidi M, Piattelli A. Zirconium implant abutments: fracture strength and influence of cyclic loading on retaining-screw loosening. Quintessence Int 2006;37:19-26.
200. Kusy RP. Orthodontic biomaterials: from the past to the present. Angle Orthod 2002;72:501-512.
201. Keith O, Kusy RP, Whitley JQ. Zirconia brackets: an evaluation of morphology and coefficients of friction. Am J Orthod Dentofacial Orthop 1994;106:605-614.
202. Springate SD, Winchester LJ. An evaluation of zirconium oxide brackets: a preliminary laboratory and clinical report. Br J Orthod 1991;18:203-209.
203. Winchester LJ. Bond strengths of five different ceramic brackets: an *in vitro* study. Eur J Orthod 1991;13:293-305.
204. Kittipibul P, Godfrey K. *In vitro* shearing force testing of the Australian zirconia-based ceramic Begg bracket. Am J Orthod Dentofacial Orthop 1995;108:308-315.
205. Matsubara S, Tanne K, Shibaguchi T, Sakuda M, Takahashi J, Kimura H. [Changes in efficiency of orthodontic tooth movement resulting from differences in bracket materials]. Osaka Daigaku Shigaku Zasshi 1990;35:355-364.
206. Saunders CR, Kusy RP. Surface topography and frictional characteristics of ceramic brackets. Am J Orthod Dentofacial Orthop 1994;106:76-87.
207. Bishara SE, Trulove TS. Comparisons of different debonding techniques for ceramic brackets: an *in vitro* study. Part II. Findings and clinical implications. Am J Orthod Dentofacial Orthop 1990;98:263-273.
208. Douglass JB. Enamel wear caused by ceramic brackets. Am J Orthod Dentofacial Orthop 1989;95:96-98.
209. Garvie RC, Hannink RH, Pascoe RT. Ceramic Steel? Nature 1975;258:703-704.
210. Sato T, Shimada M. Transformation of yttria-doped tetragonal ZrO_2 polycrystals by annealing in water. J Amer Ceram Soc 1985;86:356-359.
211. Ban S, Sato H, Suehiro Y, Nakanishi H, Nawa M. Biaxial flexure strength and low temperature degradation of Ce-TZP/Al_2O_3 nanocomposite and Y-TZP as dental restoratives. J Biomed Mater Res B Appl Biomater 2008;87:492-498.
212. Rieger W. KS, Weber W. Processing and properties of zirconia ceramics for dental applications. Spectrum Dialoge 2008;7:2-11.
213. Rahaman MN, Li Y, Bal BS, Huang W. Functionally graded bioactive glass coating on magnesia partially stabilized zirconia (Mg-PSZ) for enhanced biocompatibility. J Mater Sci Mater Med 2008;19:2325-2333.
214. Kim HW, Knowles JC, Li LH, Kim HE. Mechanical performance and osteoblast-like cell responses of fluorine-substituted hydroxyapatite and zirconia dense composite. J Biomed Mater Res A 2005;72:258-268.
215. Swab J. Low temperature degradation of Y-TZP materials. J Mater Sci 1991;26:6706-6714.
216. Papanagiotou HP, Morgano SM, Giordano RA, Pober R. *In vitro* evaluation of low-temperature aging effects and finishing procedures on the flexural strength and structural stability of Y-TZP dental ceramics. J Prosthet Dent 2006;96:154-164.
217. Kim DJ, Lee MH, Lee DY, Han JS. Mechanical properties, phase stability, and biocompatibility of (Y, Nb)-TZP/Al(2)O(3) composite abutments for dental implant. J Biomed Mater Res 2000;53:438-443.
218. Ban S. Reliability and properties of core materials for all-ceramic dental restorations. Japanese Dental Science Review 2008;44:3-21.
219. Heness G, Ben-Nissan B. Innovative bioceramics. Materials Forum 2004;27:104-114.
220. Lin JD Duh JG, Lo CL. Mechanical properties and resistance to hydrothermal aging of ceria- and yttria-doped tetragonal zirconia ceramics. Mater Chem Phys 2002;87:808-818.
221. Sato H, Yamada K, Pezzotti G, Nawa M, Ban S. Mechanical properties of dental zirconia ceramics changed with sand-blasting and heat treatment. Dent Mater J 2008;27:408-414.
222. Aboushelib MN, Kleverlaan CJ, Feilzer AJ. Evaluation of a high fracture toughness composite ceramic for dental applications. J Prosthodont 2008;17:538-544.
223. Anderson RJ, Janes GR, Sabella LR, Morris HF. Comparison of the performance on prosthodontic criteria of several alternative alloys used for fixed crown and partial denture restorations: Department of Veterans Affairs Cooperative Studies project 147. J Prosthet Dent 1993;69:1-8.

224. Studart AR, Filser F, Kocher P, Gauckler LJ. *In vitro* lifetime of dental ceramics under cyclic loading in water. Biomaterials 2007;28:2695-2705.
225. Aboushelib MN, Feilzer AJ, de Jager N, Kleverlaan CJ. Prestresses in bilayered all-ceramic restorations. J Biomed Mater Res B Appl Biomater 2008;87:139-145.
226. Aboushelib MN, Kleverlaan CJ, Feilzer AJ. Microtensile bond strength of different components of core veneered all-ceramic restorations. Part II: Zirconia veneering ceramics. Dent Mater 2006;22:857-863.
227. Fischer J, Stawarczyk B, Tomic M, Strub JR, Hammerle CH. Effect of thermal misfit between different veneering ceramics and zirconia frameworks on *in vitro* fracture load of single crowns. Dent Mater J 2007;26:766-772.
228. Fischer J, Grohmann P, Stawarczyk B. Effect of zirconia surface treatments on the shear strength of zirconia/veneering ceramic composites. Dent Mater J 2008;27:448-454.
229. de Kler M, de Jager N, Meegdes M, van der Zel JM. Influence of thermal expansion mismatch and fatigue loading on phase changes in porcelain veneered Y-TZP zirconia discs. J Oral Rehabil 2007;34:841-847.
230. Aboushelib MN, Kleverlaan CJ, Feilzer AJ. Effect of zirconia type on its bond strength with different veneer ceramics. J Prosthodont 2008;17:401-408.
231. Ban S, Sato H, Yamashita D. Microstructure and mechanical properties of recent dental porcelains. Arch Bioceram Res 2006;6:58-61.
232. Weigl P, Lauer HC. Advanced biomaterials used for a new telescopic retainer for removable dentures. J Biomed Mater Res 2000;53:337-347.
233. Hermann I, Bhowmick S, Lawn BR. Role of core support material in veneer failure of brittle layer structures. J Biomed Mater Res B Appl Biomater 2007;82:115-121.
234. Tsumita M, Kokubo Y, Vult von Steyern P, Fukushima S. Effect of framework shape on the fracture strength of implant-supported all-ceramic fixed partial dentures in the molar region. J Prosthodont 2008;17:274-285.
235. Kokubo Y, Tsumita M, Sakurai S, Torizuka K, Vult von Steyern P, Fukushima S. The effect of core framework designs on the fracture loads of all-ceramic fixed partial dentures on posterior implants. J Oral Rehabil 2007;34:503-507.
236. McLaren EA, Terry DA. CAD/CAM systems, materials, and clinical guidelines for all-ceramic crowns and fixed partial dentures. Compend Contin Educ Dent 2002;23:637-641,644,646.
237. De Jager N, de Kler M, van der Zel JM. The influence of different core material on the FEA-determined stress distribution in dental crowns. Dent Mater 2006;22:234-242.
238. Lee JJ, Kwon JY, Bhowmick S, Lloyd IK, Rekow ED, Lawn BR. Veneer vs. core failure in adhesively bonded all-ceramic crown layers. J Dent Res 2008;87:363-366.
239. De Jager N PP, Feilzer AJ. The influence of design parameters on the FEA-determined stress distribution in CAD-CAM produced all-ceramic dental crowns. Dent Mater 2005;21:242-251.