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Contemporary all-ceramic fixed partial dentures: a review

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Several restorative systems for fabricating all-ceramic fixed partial dentures (FPDs) have been tested and are being tested in clinical studies for their long-term success. Yttrium tetragonal zirconia polycrystals (Y-TZP)-based systems are the most recent version being tested. With the emphasis on the use of computer-assisted design/computer assisted-manufacturing (CAD/CAM) technology, various production techniques have been developed for enhancing the fabrication of consistent and predictable restorations in terms of strength, marginal fit, and esthetics. Because clinical data evaluating their performance are limited, the use of these systems in a predictable manner is considered by many to be controversial [1], and metal-ceramic FPDs remain the gold standard in terms of predictability.

In a recent clinical retrospective study evaluating 515 metal-ceramic FPDs, Walton [2] calculated that the cumulative survival rate of FPDs was 96% for 5 years, 87% for 10 years, and 85% for 15 years of service. This cumulative survival rate was not related to the number of units restored by an FPD. Two hundred ninety-nine of the evaluated FPDs were three-units. In light of these findings demonstrating the expected survival rate of the current standard of care, all-ceramic FPDs should demonstrate at least a similar survival rate in clinical studies to be considered as a predictable restorative alternative.

Walton also reported that modes of failure for metal-ceramic FPDs were tooth fracture (38%), periodontal breakdown (27%), loss of retention (13%), and caries (11%) [3]. An earlier study showed that the primary cause of failure was dental caries (38%); other modes of failure included delamination of the veneering porcelain, cement wash, defective

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margins, abutment fracture, post and core/root fracture, periodontal disease/abutment mobility, and periapical lesion resulting from pulpal involvement [4].

Campbell and Sozio [5] found, in an in vitro study evaluating statically loaded all-ceramic and metal-ceramic FPDs, that ceramic FPDs developed vertical cracks in the connector region before failing, whereas the metal-ceramic FPDs developed cracks at the intaglio surface of the pontic before failing. Kelly et al [6] demonstrated in vitro and in vivo that the exclusive mode of failure in all-ceramic FPDs was a fracture of the connectors. These findings were further supported in several clinical studies evaluating all-ceramic FPDs [7–10]. Thus, the primary cause of failure reported for all-ceramic FPDs differs from that reported for the metal-ceramic FPDs. To prevent such a failure, the connectors of all-ceramic FPDs must have sufficient height and width. The strength and therefore the minimal critical dimensions of these connectors are exclusively dependent on the type of ceramic material used for the core material.

To ensure long-term success of metal-ceramic FPDs, the minimal critical dimensions recommended for the connectors are 2.5 mm (occlusogingival height) by 2.5 mm (buccolingual width), providing a connector surface area of 6.25 mm^2 [11,12]. These dimensions are most likely to be successfully achieved in the anterior and posterior segments, thus making the proper diagnosis and patient selection for this type of restoration relatively simple. This is not the case for all-ceramic FPDs. Due to their primary mode of failure and the brittleness of ceramics, the required connector dimensions are larger than the ones recommended for metal-ceramic FPDs. This may be a major contributing factor in restricting the versatility of their use. Therefore, appropriate diagnosis, patient selection, and conception of the requirements of proper ceramic framework design are crucial for the success of these restorations.

Framework design

The clinical fracture resistance of FPDs is related to the size, shape, and position of the connectors and to the span of the pontic. The basis for the proper design of the connectors and the pontic is the law of beams: Deflection of a beam increases as the cube of its length, it is inversely proportional to its width, and it is inversely proportional to the cube of its height [13]. A three-point bending test is one of the most commonly used tests to determine the modulus of rupture or the transverse flexural strength of a rectangular beam made of a brittle material [14,15]. When occlusal forces are applied directly through the long axis of an all-ceramic bridge connector, compressive stresses develop at the occlusal aspect of the connector at the marginal ridge, and tensile stresses develop at the gingival surface of the connector. These tensile stresses contribute to the propagation of microcracks located at the gingival surface of the connector through the core material in an occlusal direction and may lead to a fracture. The most common mode of failure of all-ceramic FPDs is a fracture of the connectors, with 70% to 78% of the cracks originating from the interface between the core and the ceramics [6]. Oh et al [16] demonstrated in a finite element analysis and a fractographic analysis that connector fracture was initiated at the gingival embrasure and that a larger radius of curvature at the gingival embrasure reduces the concentration tensile stresses, thus affecting the fracture resistance of the FPD. Oh and Anusavice [17] demonstrated the same in an in vitro study. To promote achieving the required connector dimensions without compromising the health of the supporting tissues, it was suggested to fabricate the gingival and lingual aspects of the connectors out of the framework material exclusively [18]. In addition, the span of the pontic should not exceed the length of a first mandibular molar, depending on the properties of core material and framework design.

Evolution

A high-alumina ceramic for the fabrication of FPD pontic structures was first introduced by McLean in 1967 [19]. In 1982, he introduced the platinum-bonded alumina FPD to reduce the problem of fracture through the connector area while eliminating the traditional cast-metal framework [20]. However, this restorative option was not feasible due to a high rate of failure at the connector sites.

New developments in dental ceramics have led to the introduction of new systems for all-ceramic FPDs. The In-Ceram alumina system (Vita Zahnfabric, Bad Sackingen, Germany), which uses high-temperature, sintered-alumina glass-infiltrated copings for all-ceramic crowns, was introduced for the fabrication of three-unit anterior FPDs [21]. To fabricate the framework the ceramist can use the slip-casting technique or copy milling technique with prefabricated partially sintered blanks. The transverse flexural strength of the framework material was demonstrated to be about 446 MPa [22]. With this system, the minimal critical dimensions for the connectors are 4 mm occlusal/gingivally and 3 mm buccal/lingually [18].

The Empress II system (Ivoclar North America, Amherst, New York) uses a lithium-disilicate glass framework that is veneered with fluoroapatite-based veneering porcelain. The framework is fabricated with the lost-wax and heat-pressure technique or is milled out of prefabricated blanks. The transverse flexural strength of the framework material ranges between 350 and 400 MPa [23]. Although these glass-containing materials allow the fabrication of relatively translucent restorations, it is recommended that these restorations be etched and adhesively cemented to enhance their strength. The system is confined to fabricating three-unit FPDs that replace a missing tooth anterior to the second premolar. The minimal critical dimensions for the connectors are 4 to 5 mm occlusal/gingivally and 4 mm buccal/lingually [8].

The Procera AllCeram Bridges system (Nobel Biocare, Goteborg, Sweden) uses a densely sintered high-purity aluminum-oxide framework [24]. The framework is waxed-up as two single copings on the abutment teeth and a central pontic, which are then scanned in the same manner as in the fabrication of densely sintered high-purity aluminum-oxide crowns. They are milled individually and are fused together with a special veneering ceramics at the connector. The transverse flexural strength of the framework material ranges between 500 and 650 MPa [25,26]. The minimal critical dimensions for the connectors are 3 mm occlusal/gingivally with a surface area of 6 mm^2 [27].

The In-Ceram Zirconia system (Vita Zahnfabric) uses a glass-infiltrated alumina with 35% partially stabilized zirconia framework. To fabricate the framework, the ceramist may use the slip-casting technique or copy-milling technique with prefabricated partially sintered blanks. The transverse flexural strength of the framework material ranges between 600 and 800 MPa [21,28]. For the In-Ceram Zirconia restoration, the recommended minimal critical dimensions for the connectors are 4 mm occlusal/gingivally and 3 mm of buccal/lingually. Due to esthetic limitations of the system resulting from the opacity of the framework, the system is recommended for fabricating posterior ceramic FPDs [28]. The lack of required space for desired connector dimensions frequently contraindicates the fabrication of an all-ceramic FPD.

Recent core materials and technologies

The most recent core materials for all-ceramic FPDs are the yttrium tetragonal Y-TZP-based materials. Y-TZP-based materials were initially introduced for biomedical use in orthopedics for total hip replacement and were highly successful because of the material's excellent mechanical properties and biocompatibility [1]. In the early 1990s, the use of Y-TZP expanded into dentistry (endodontic posts and implant abutments) [29–32], and Y-TZP is currently being evaluated as an alternative core material for full-coverage restorations such as all-ceramic crowns and all-ceramic FPDs [33–35].

Yttrium oxide is a stabilizing oxide added to pure zirconia to stabilize it at room temperature and to generate a multiphase material known as partially stabilized zirconia. The exceptional mechanical properties of Y-TZP (high initial strength and fracture toughness) are due to the unique physical property of partially stabilized zirconia. Tensile stresses acting at the crack tip induce a transformation of the metastable tetragonal zirconium oxide form into the monoclinic form. This transformation is associated with a local increase of 3% to 5% in volume. This increase in volume results in localized compressive stresses being generated around and at the tip of the crack that counteract the external tensile stresses acting on the fracture tip [36]. This physical property is known as transformation toughening.

The long-term stability of ceramics is closely related to subcritical crack propagation and stress corrosion caused by water in the saliva reacting with the glass, resulting in decomposition of the glass structure, which leads to increased crack propagation in glass-containing systems. However, glass-free systems having a polycrystalline microstructure, such as Y-TZP, do not exhibit this phenomenon. Therefore, their long-term stability may be enhanced. In in vitro studies, Y-TZP bars demonstrated a flexural strength of 900 to 1200 MPa [36–38]. In vitro studies on Y-TZP FPDs (with different connector dimensions) under static load demonstrated fracture resistance between 1800 to more than 2000 N. Under cyclic load simulating a 5-year clinical load, the fracture resistance of posterior three-unit bridges cemented with glass ionomer cement was 1457 N, which was well beyond the 1000 N required [39,40].

Patient selection and treatment planning

As part of the diagnosis and decision-making process in selecting the appropriate treatment option for an individual patient, the edentulous space must be evaluated in terms of the available interocclusal distance. To facilitate patient selection for all-ceramic FPDs, one must confirm adequate prospective height for the framework material and veneering ceramics before determining the restorative system of choice. A 4-mm clinical measurement with periodontal probe from interproximal papilla to the marginal ridge of the prospective abutment indicates adequate connector height for most contemporary systems for all-ceramic FPDs (Fig. 1). At times the available space for the connector may be restricted by reduced interocclusal distance, which may make it difficult to achieve the required connector dimensions without compromising the biologic demands of open embrasures needed for facilitating plaque control and adequate oral hygiene (Fig. 2). The following clinical scenarios lead to reduced interocclusal distance; therefore, alternative treatment options rather than all-ceramic FPDs must be considered [27].

1. A deep vertical overlap with a reduced horizontal overlap leading to a deep bite in the anterior maxillary segment (Class II Division II) that may not allow sufficient labiolingual connector width
2. An opposing tooth that is supraerupted into the edentulous space that cannot be corrected with minor enameloplasty only and that may be accompanied with mesial drift of a prospective molar abutment tooth into the edentulous space
3. Prospective abutment teeth with short clinical crowns that may restrict the height of the connector

The concentration of heavy stresses in the connector area increases the risk of catastrophic fracture. Therefore, it is mandatory to evaluate prospective abutments in terms of their periodontal health with an emphasis

Fig. 1. Preoperative lateral view in maximum intercuspation. The opposing teeth did not dramatically supraerupt in a manner that contraindicates the fabrication of a Y-TZP–based all-ceramic FPD.

on abutment mobility. Prospective abutments exhibiting increased mobility should not be used as a foundation for all-ceramic FPDs. The use of all-ceramic FPDs with a cantilever design is questionable (the pontic acts as a lever that is depressed under occlusal forces) due to the possibility of developing heavy stress at the connector. Finally, heavy bruxers who exhibit parafunctional activity should not receive all-ceramic FPDs.

Design and manufacturing of Y-TZP–based FPD frameworks

A Y-TZP–based FPD framework is designed using conventional waxing techniques or CAD. Optimal CAD software allows technicians to custom design an FPD framework while combining traditional concepts of design

Fig. 2. Preoperative lateral view of a patient missing his left mandibular first molar. A measurement of the distance between the marginal ridge and the free gingival margin confirmed that adequate prospective connector height (4 mm) exists for the fabrication of a Y-TZP–based all-ceramic FPD.

with material-derived requirements. Several Y-TZP–based restorative systems for crowns and FPDs have been described in scientific abstracts and in peer-reviewed articles.

The Cercon system (Dentsply Ceramco, Burlington, New Jersey) requires conventional waxing techniques for designing the Y-TZP–based infrastructure. The DCS-Precident, DC-Zirkon (Smartfit Austenal, Chicago, Illinois) and the Lava (3M ESPE, St. Paul, Minnesota) systems each use a different type of CAD technology with different features and design options (Fig. 3) [33–35]. Once the design of the framework is completed, the data are transferred to a milling unit for fabricating the framework. The data are transferred from the CAD unit to the CAM unit, or a conventional wax-pattern is scanned as with the Cercon system. The Cercon system and the Lava system use partially sintered Y-TZP–based blanks for milling the infrastructures, whereas DCS-Precident, DC-Zirkon infrastructures are milled from fully sintered Y-TZP–based blanks. With a partially sintered milled framework, the size has been increased to compensate for shrinkage (20% to 25%) that occurs during final sintering. The milling process is faster, and the wear and tear of hardware is less than when milling from a fully sintered blank [33–35]. Studies show that clinically acceptable marginal fit is maintained (Figs. 4, 5) [41,42]. The proponents of partially sintered frameworks claim that microcracks may be introduced to the framework during the milling procedure, whereas the proponents of milling of a fully sintered blank claim that the marginal fit is superior because no shrinkage is involved in the process.

Features of Y-TZP–based restorations

Most of the advantages of Y-TZP–based FPDs described here validate the use of Y-TZP–based materials for all-ceramic crowns and all-ceramic

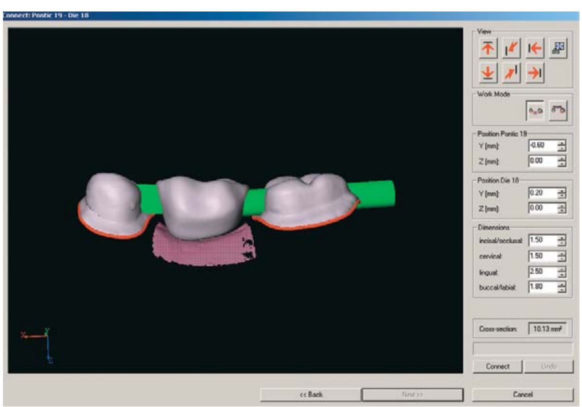

Fig. 3. A view of the CAD FPD framework designed on the computer (Lava; 3M ESPE, St. Paul, Minnesota).

Fig. 4. Lingual view of the completed framework fitted to the working dies. Note the excellent marginal fit.

FPDs. The use of all-ceramic restorations increases the depth of translucency and light transmission across the entire restoration [43]. Some of the zirconia-based systems use a single white shade for the core (eg, Cercon, DCS-Precident). The Lava Y-TZP core is relatively translucent and has a masking ability that allows successful coverage of metal cores or discolored teeth. Once milled, it can be colored into one of seven shades (corresponding to the Vita-Lumin shade guide) before the final sintering procedures. This allows the development of the shade of the restoration from its intaglio surface all the way to the outer aspect of the veneering porcelain (Fig. 6). The ability to control the shade of the core may also eliminate the need to veneer the lingual and gingival aspects of the connectors in cases were the interocclusal distance is limited and the required connector dimensions are barely achieved. In addition, the palatal aspect of anterior crowns and FPDs may be fabricated exclusively of the

Fig. 5. Buccal view of the completed framework fitted to the working dies. Note the excellent marginal fit.

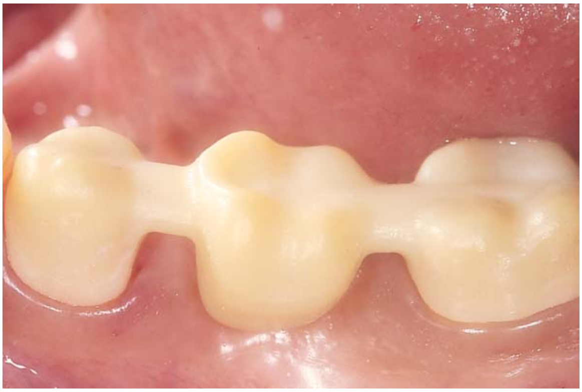

Fig. 6. Buccal view of the framework try-in. Note the excellent blending of the framework with the gingival tissue and the open gingival embrasures for oral hygiene maintenance.

core material in patients who lack space for lingual veneering porcelain [44]. Special feldspathic veneering porcelains were designed to match the Y-TZP–based frameworks in terms of physical and optical properties, with a coefficient of thermal expansion closely matched (Fig. 7) [44].

Clinicians may place the finish line of a tooth preparation at the free gingival margin or slightly below it (0.5 mm) without compromising the esthetic result (Fig. 8). This reduces the possibility of iatrogenic periodontal disease [45–47]. Moreover, the ability to place the finish line at or below the free gingival margin facilitates the making of an accurate impression.

Ceramic materials in general are considered to be great insulators. All-ceramic systems have reduced thermal conductivity, resulting in less thermal sensitivity and potential pulpal irritation [8].

Fig. 7. The completed restoration before cementation. Note the blending of the Y-TZP–based framework with the veneering porcelain.

Fig. 8. Postoperative lateral view in maximum intercuspation 6 months postcementation of the Y-TZP–based FPD.

A small percentage of the population is hypersensitive to dental alloys containing noble and base metals, such as palladium and nickel. Metal-free ceramic systems eliminate this problem [48–53]. The high biocompatibility of Y-TZP was evaluated in in vitro and in vivo studies with no reported local or systemic adverse reactions to the material [54–57]. The findings of a recent study also demonstrated that fewer bacteria accumulated around Y-TZP than titanium [58].

YTZ-P–based cores present with a metal-like radiopacity that enhances radiographic evaluation of the restoration in terms of marginal integrity, adequate excess cement removal, and prospective secondary decay (Fig. 9) [44].

As a result of their mechanical and physical properties YTZ-P-based FPD frameworks require a relatively small connector area compared with their predecessors, ranging between 7 and 16 mm^2 [27].

Limitations

The main limitation of Y-TZP–based all-ceramic FPDs is that in many cases their use may be contraindicated because of a lack of required dimensions for the prospective connector resulting from restricted interocclusal distance, prospective abutment mobility, or severe parafunction. When all-ceramic FPD systems do not fit precisely, a new definitive impression must be made because they cannot be sectioned and soldered like metal-ceramic FPDs. The other limitation is the lack of long-term clinical data on the success of these restorations.

Clinical procedures

Clinical procedures and radiographic evaluation are similar to those used with metal-ceramic FPDs. Metal-ceramic–like preparation design, which

Fig. 9. Postoperative radiograph demonstrates the metal-like radiopacity of the Y-TZP–based FPD.

is within the clinician's comfort zone, is recommended with rounded line angles and rounded finish lines, such as deep chamfer or a rounded shoulder. The finish line may be placed at the free gingival margin or slightly below it (0.5 mm) when possible without compromising the esthetic result [44].

With Y-TZP–based materials, adhesive cementation is not mandatory, and traditional cementation procedures can be used predictably. Adhesive cementation may be technique sensitive, especially if the finish line is placed deep into the gingival sulcus because of previous restorations, decay, or the need to enhance retention. In these cases, adequate moisture control may not be successful, leading to a compromised adhesive cementation procedure and compromising the longevity of the restoration [44].

Summary

Because of their material-inherent advantages, Y-TZP–based all-ceramic restorative systems may allow clinicians to use traditional clinical procedures similar to those used in the fabrication of metal-ceramic restorations in terms of preparation design and cementation procedures. With Y-TZP–based systems that use a CAD/CAM technology, ceramists use new techniques and technologies in addition to traditional ones. Such new technologies may allow the production of consistent high-quality Y-TZP frameworks in terms of design and fabrication, strength, fracture toughness, and stress-corrosion resistance. They are esthetic, have clinically acceptable marginal fit, and allow the ceramist to use traditional veneering procedures with the compatible esthetic porcelain. In addition, such systems may prove to be simple to handle and less technique sensitive from a clinical standpoint while providing patients with esthetic and functional restorations. Although clinical data on the success of these restorations are limited, anecdotal evidence and initial observations made in ongoing clinical studies are promising. The long-term results of these studies are paramount to the assessment of their long-term success and for the establishment of more specific guidelines for proper patient selection that will ensure long-term predictable esthetic and functional success.

References

[1] Raigrodski AJ, Chiche GJ. The safety and efficacy of anterior ceramic fixed partial dentures: a review of the literature. J Prosthet Dent 2001;86:520–5.
[2] Walton TR. An up to 15-year longitudinal study of 515 metal-ceramic FPDs: part 1. Outcome. Int J Prosthodont 2002;15:439–45.
[3] Walton TR. An up to 15-year longitudinal study of 515 metal-ceramic FPDs: part 2. Modes of failure and influence of various clinical characteristics. Int J Prosthodont 2003; 16:177–82.
[4] Libby G, Arcuri MR, LaVelle WE, Hebl L. Longevity of fixed partial dentures. J Prosthet Dent 1997;78:127–31.
[5] Campbell SD, Sozio RB. Evaluation of the fit and strength of an all-ceramic fixed partial denture. J Prosthet Dent 1988;59:301–6.
[6] 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;74:1253–8.
[7] Sorensen JA, Kang SA, Torres TJ, Knode H. In-Ceram fixed partial dentures: three-year clinical trial results. J Cal Dent Assoc 1998;26:207–14.
[8] Sorensen JA, Curz M, Mito WT, Raffeiner O, Meredith HR, Foser HP. A clinical investigation on three-unit fixed partial dentures fabricated with a lithium disilicate glass-ceramic. Pract Periodont Aesthet Dent 1998;11:95–106.
[9] Vult von Steyern P, Jonsson O, Nilner K. Five year evaluation of posterior all-ceramic three-unit (In-Ceram) FPDs. Int J Prosthodont 2001;14:379–84.
[10] Olsson KG, Furst B, Andersson B, Carlsson GE. A long-term retrospective and clinical follow-up study of In-Ceram Alumina FPDs. Int J Prosthodont 2003;16:150–6.
[11] Miller LL. Framework design in ceramo-metal restorations. Dent Clin North Am 1977;21: 699–716.
[12] McLean JW. The science and art of dental ceramics, vol. 2. Bridge design and laboratory procedures in dental ceramics. Chicago: Quintessence; 1982.
[13] DuPont R. Large ceramo-metallic restorations. Int Dent J 1968;18:288–308.
[14] Seghi RR, Daher T, Caputo A. Relative flexural strength of dental restorative ceramics. Dent Mater 1990;6:181–4.
[15] White SN, Caputo AA, Vidjak FMA, Seghi RR. Moduli of rupture of layered dental ceramics. Dent Mater 1994;10:52–8.
[16] Oh W, Gotzen N, Anusavice KJ. Influence of connector design on fracture probability of ceramic fixed partial dentures. J Dent Res 2002;81:623–7.
[17] Oh W, Anusavice KJ. The effect of connector design on the fracture resistance of all-ceramic fixed partial dentures. J Prosthet Dent 2002;87:536–42.
[18] McLaren EA. All-ceramic alternatives to conventional metal-ceramic restorations. Compend Contin Educ Dent 1998;19:307–25.
[19] McLean JW. High-alumina ceramics for bridge pontic construction. Br Dent J 1967;123: 571–7.
[20] McLean JW. Alumina reinforced ceramics special applications. In: The science and art of dental ceramics, vol. 2. Bridge design and laboratory procedures in dental ceramics. Chicago: Quintessence; 1982. p. 474–9.

[21] Sorensen JA, Knode H, Torres TJ. In-ceram all-ceramic bridge technology. Quintessence Dent Techonol 1992;15:41–6.
[22] Seghi RR, Sorensen JA. Relative flexural strength of six new ceramic materials. Int J Prosthodont 1995;8:239–46.
[23] Sorensen JA. The IPS Empress 2 system: defining the possibilities. Quintessence Dent Technol 1999;22:153–63.
[24] Oden A, Andersson M, Krystek-Ondracek I, Magnusson D. Five-year clinical evaluation of Procera AllCeram crowns. J Prosthet Dent 1998;80:450–6.
[25] White SN, Caputo AA, Li ZC. Modulus of rupture of the Procera Ceramic system. J Esthet Dent 1996;8:120–6.
[26] Zeng K, Oden A, Rowcliffe D. Flexure tests on dental ceramics. Int J Prosthodont 1996;9: 434–9.
[27] Raigrodski AJ, Salzer AM. Clinical considerations in case selection for all-ceramic fixed partial dentures. Pract Proced Aesthet Dent 2002;14:411–9.
[28] McLaren EA, White SN. Glass-infiltrated zirconia/alumina-based ceramic for crowns and fixed partial dentures: clinical and laboratory guidelines. Quintessence Dent Technol 2000; 23:63–76.
[29] Jeong SM, Ludwig K, Kern M. Investigation of the fracture resistance of three types of zirconia posts in all-ceramic post-and-core restorations. Int J Prosthodont 2002;15:154–8.
[30] Edelhoff D, Sorensen JA. Retention of selected core materials to zirconia posts. Oper Dent 2002;27:455–61.
[31] Heydecke G, Butz F, Hussein A, Strub JR. Fracture strength after dynamic loading of endodontically treated teeth restored with different post-and-core systems. J Prosthet Dent 2002;87:438–45.
[32] Bonilla HA, Sullivan D. Clinical indication and techniques for the ZiReal post. Compend Contin Educ Dent Suppl 2001;8:3–7.
[33] 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 Compute Dent 2001;4:84–106.
[34] Besimo CE, Spielmann HP, Rohner HP. Computer-assisted generation of all-ceramic crowns and fixed partial dentures. Int J Computerized Dent 2001;4:243–62.
[35] Suttor D, Bunke K, Hoescheler S, Hauptmann H, Hertlein G. Lava: the system for all-ceramic ZrO_2 crown and bridge frameworks. Int J Computerized Dent 2001;4:195–206.
[36] Christel P, Meunier A, Heller M. Mechanical properties and short term in-vivo evaluation of yttrium-oxide-partially-stabilized zirconia. J Biomed Mater Res 1989;23:45–61.
[37] Hauptmann H, Suttor D, Frank S, Hoescheler H. Material properties of all-ceramic zirconia prostheses. J Dent Res 2000;79:507.
[38] Rountree P, Nothdurft F, Pospiech P. In-vitro investigations on the fracture strength of all-ceramic posterior bridges of ZrO_2-ceramic [abstract]. J Dent Res 2001;80:57.
[39] Suttor D, Hauptmann H, Frank S, Hoescheler S. Fracture resistance of posterior all ceramic zirconia bridges [abstract]. J Dent Res 2001;80:640.
[40] 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;14:231–8.
[41] Hertlein G, Hoescheler H, Frank S, Suttor D. Marginal fit of CAD/CAM manufactured all ceramic zirconia prostheses [abstract]. J Dent Res 2001;80:492.
[42] Hertlein G, Kraemer M, Sprengart T, Watzek K. Milling time vs. marginal fit of CAD/CAM-manufactured zirconia restorations [abstract]. J Dent Res 2003.
[43] Chiche GJ, Pinault A. Esthetics of anterior fixed prosthodontics. Carol Stream (IL): Quintessence; 1994.
[44] Raigrodski AJ. Clinical and laboratory considerations for the use of CAD/CAM Y-TZP-based restorations. Pract Proced Aesthet Dent 2003;15:469–76.

[45] Gargiulo AW, Wentz FM, Orban B. Dimensions and relationships of the dentogingival junction in humans. J Periodontol 1961;32:261–7.
[46] Silness J. Periodontal conditions in patients treated with dental bridges: 3. The relationship between the location of the crown margin and periodontal condition. J Periodontol Res 1970;5:225–9.
[47] Newcomb GM. The relationship between the location of subgingival crown margins and gingival inflammation. J Periodontol 1974;45:151–4.
[48] Moffa JP, Guckes AD, Okawa MT, Lilly GE. An evaluation of nonprecious alloys for use with porcelain veneers: part II. Industrial safety and biocompatability. J Prosthet Dent 1973;30:432–41.
[49] Liu TZ, Lee SD, Bhatnagar RS. Toxicity of palladium. Toxicol Lett 1979;4:469–73.
[50] Council on Dental Materials, Instruments, and Equipment. Biological effects of nickel-containing dental alloys. J Am Dent Assoc 1982;104:501–5.
[51] Purt R. Palladium ceramic alloys: possible health hazards. Quintessence Dent Technol 1987;11:35–41.
[52] Lamster IB, Kalfus DI, Steigerwald PJ, Chasens AI. Rapid loss of alveolar bone associated with nonprecious alloy crowns in two patients with nickel hypersensitivity. J Periodontol 1987;58:486–92.
[53] Hansen PA, West LA. Allergic reaction following the insertion of pd-cu-au fixed partial denture: a clinical report. J Prosthodont 1997;6:144–8.
[54] Piconi C, Maccuro G. Zirconia as a ceramic biomaterial. Biomater 1999;20:1–25.
[55] Ichikawa Y, Akagawa Y, Nikai H, Tsuru H. Tissue compatibility and stability of a new zirconia ceramic in vivo. J Prosthet Dent 1992;68:322–6.
[56] Josset Y, Oum'Hamed Z, Zarrinpour A, Lorenzato M, Adnet JJ, Laurent-Maquin D. In vitro reactions of human osteoblasts in culture with zirconia alumina ceramics. J Biomed Mater Res 1999;47:481–93.
[57] Covacci V, Bruzzese N, Maccauro G, Andreassi C, Ricci GA, Piconi C, et al. In vitro evaluation of the mutagenic and carcinogenic power of high purity zirconia ceramic. Biomater 1999;20:371–6.
[58] Rimondini L, Cerroni L, Carrasi A, Torricelli P. Bacterial colonization of zirconia ceramic surfaces: an in vitro and in vivo study. Int J Oral Maxillofac Implants 2002;17:793–8.