

# All-ceramic materials in dentistry

Samarjit Singh Teja, Prerna Hoogan Teja<sup>1</sup>

Access this article online
Quick Response Code:

Website: www.sidj.org
DOI: 10.4103/2454-3160.177930

## Abstract:

In dentistry, ceramics are often referred to as nonmetallic, inorganic structures primarily containing compounds of oxygen with one or more metallic or semimetallic elements. They are composed of sodium, potassium, calcium, magnesium, aluminum, silicon, phosphorus, zirconium, and titanium. Structurally, dental ceramics contain a crystal phase and a glass phase based on the silica structure, characterized by silica tetrahedra, containing central Si<sup>4+</sup> ion with four O<sup>-</sup> ions. Biocompatibility, esthetics, durability, and easier customization properties have led to the increased usage of ceramics. The specialty of ceramic teeth is its ability to mimic the natural tooth in color and translucency along with its strength. Ceramics have excellent intraoral stability and wear resistance adding to their durability. Basically, the inorganic composition of teeth and bones are ceramics which is hydroxyapatite. Over the past few years, the technological evolution of ceramics for dental applications has been incredible, as new materials and processing techniques are being introduced. The improvement in strength, as well as toughness, has made it possible to expand the range of indications to long-span fixed partial prostheses, implant abutments, and implants. While porcelain-based materials are still a major component in dental science, there have been moves to replace metal ceramics systems with all-ceramic systems. Numerous all-ceramics are being developed which is highly esthetic, biocompatible to tissue, and long-lasting in nature. Advances in computer-aided design/computer-aided manufacturing technologies have led to immense popularity of high-strength ceramic materials. These materials are highly esthetic, biocompatible to tissue, and long-lasting in nature. In this review, we will discuss all-ceramic materials which are used in dentistry.

**Key words:** All-ceramic, alumina, computer-aided design/computer-aided manufacturing, silicate, zirconia

Recent trends show a shift from metal-ceramics to metal-free restorations in the dental field. Several types of all-ceramic materials have been developed to meet the increased demands of patients and dentists, which are highly esthetic, biocompatible, and long-lasting.<sup>[1]</sup> Silicate and glass ceramics are used as a veneer for metal or all-ceramic cores. High-strength ceramics such as aluminum and zirconium oxide were developed as a core material for crowns and fixed partial dentures (FPDs) to extend its range to high load bearing areas.<sup>[2]</sup> Due to advances in computer-aided design (CAD)/computer-aided manufacturing (CAM) technologies, high-strength ceramic materials have gained immense popularity. Zirconia, especially yttria-containing tetragonal zirconia polycrystal (Y-TZP), offering increasingly greater performance from a mechanical standpoint, has expanded its range from single crowns and short-span FPDs to multiunit and full-arch zirconia frameworks as well as implant abutments and complex implant superstructures to support fixed and removable prostheses.<sup>[3,4]</sup> This overview presents the current knowledge of all-ceramic materials, their composition and processing mechanisms, and possible future trends.

## HEAT-PRESSED CERAMICS

In the early 1990s, the lost wax press technique was used as an innovative processing method for producing all-ceramic restorations. The dental technicians are usually familiar with this technique, which is commonly used to cast dental alloys. In addition, the equipment needed to heat-press dental ceramics is relatively inexpensive. The first generation of heat-pressed dental ceramics contains leucite as a reinforcing crystalline phase, whereas the second generation is lithium-disilicate based.

### Leucite glass ceramics

The first generation of heat-pressed dental ceramics contain leucite as a reinforcing crystalline in a concentration of 35–45 vol%.<sup>[5]</sup>

This is an open access article distributed under the terms of the Creative Commons Attribution-NonCommercial-ShareAlike 3.0 License, which allows others to remix, tweak, and build upon the work non-commercially, as long as the author is credited and the new creations are licensed under the identical terms.

**For reprints contact:** reprints@medknow.com

**How to cite this article:** Teja SS, Teja PH. All-ceramic materials in dentistry. Saint Int Dent J 2015;1:91-5.

Department of  
Prosthodontics,  
Swami Devi Dyal  
Hospital and Dental  
College, Panchkula,  
Haryana, <sup>1</sup>Department  
of Orthodontics and  
Dentofacial Orthopedics,  
Bhojia Dental College  
and Hospital, Bhud,  
Baddi, Himachal  
Pradesh, India

### Address for correspondence:

Dr. Prerna Hoogan Teja,  
HNO 771/A, Joginder  
Vihar, Phase II,  
Mohali - 160 055,  
Punjab, India.  
E-mail: den\_capricorn@  
yahoo.co.in

The molding procedure is conducted at 1080°C in a special, automatically controlled furnace. The leucite crystals are formed through a controlled surface crystallization process in the  $\text{SiO}_2\text{-Al}_2\text{O}_3\text{-K}_2\text{O}$  glass system. Because of the difference in the coefficient of thermal expansion (CTE) between leucite crystals and glassy matrix, tangential compressive stresses develop around the crystals on cooling. These stresses lead to crack deflection and improved mechanical performance.<sup>[6]</sup> These materials exhibit a flexural strength of 120–180 MPa and a CTE of  $15\text{--}18.5 \times 10^{-6}/\text{K m/m}$ .<sup>[7]</sup> Examples of leucite-reinforced glass ceramics are VITA VMK 68 (VITA Zahnfabrik, Bad Sackingen, Germany), Finesse All-Ceramic (Dentsply, York, PA, USA), Optec OPC (Jeneric, Wallingford, CT, USA), and IPS Empress (Ivoclar Vivadent, Schaan, Principality of Liechtenstein). This material is suitable for fabrication of inlays, onlays, veneers, and crowns. Favorable clinical long-term data with high survival rates has been described for IPS Empress inlays, onlays (90% after 8 years),<sup>[8]</sup> veneers (94.4% after 12 years),<sup>[9]</sup> and crowns (95.2% after 11 years)<sup>[10]</sup> in the dental literature. Leucite glass ceramics can also be machined with various CAD/CAM systems. Multicolored blocks have been recently developed to reproduce color transitions and shading as well as different levels of translucency to reproduce natural teeth.<sup>[11]</sup> But with the introduction of lithium disilicate glass ceramics, which have significantly improved mechanical and esthetic properties, the use of leucite-reinforced glass ceramics has declined.

### Lithium disilicate glass ceramics

The second generation heat-pressed ceramics contain about 65 vol% lithium disilicate as the main crystalline phase.<sup>[6]</sup> A significantly higher strength of 350 MPa was achieved with a glass ceramic of the  $\text{SiO}_2\text{-Li}_2\text{O-K}_2\text{O-ZnO-P}_2\text{O}_5\text{-Al}_2\text{O}_3\text{-La}_2\text{O}_3$  system by precipitating lithium disilicate ( $\text{Li}_2\text{Si}_2\text{O}_5$ ) crystals. High-temperature X-ray diffraction studies revealed that both lithium metasilicate ( $\text{Li}_2\text{SiO}_3$ ) and cristobalite form during the crystallization process before the growth of lithium disilicate ( $\text{Li}_2\text{Si}_2\text{O}_5$ ) crystals.<sup>[12]</sup> The final microstructure consists of, 5  $\mu\text{m}$  in length and 0.8  $\mu\text{m}$  in diameter, highly interlocked lithium disilicate crystals. Tangential compressive stresses develop around the crystals due to thermal expansion mismatch between lithium disilicate crystals and glassy matrix, potentially responsible for crack deflection and strength increase. Multiple crack deflections develop due to crystal alignment after heat pressing of lithium disilicate glass ceramic. The lithium disilicate ceramic was introduced as IPS Empress 2 (Ivoclar Vivadent) in 1998 and is moldable as leucite glass ceramics but at a lower temperature of 920°C. The CTE is  $10.5 \times 10^{-6}/\text{K m/m}$ .<sup>[13]</sup> High survival rates were observed for anterior and posterior IPS Empress 2 crowns (95.5% after 10 years).<sup>[14]</sup> IPS e.max Press (Ivoclar Vivadent) is the newly developed pressable lithium disilicate glass ceramic with improved physical properties (flexural strength, 440 MPa) and translucency through a different firing process in the  $\text{SiO}_2\text{-Li}_2\text{O-K}_2\text{O-ZnO-P}_2\text{O}_5\text{-Al}_2\text{O}_3\text{-ZrO}_2$  system. This can be used in a monolithic application for inlays, onlays, and posterior

crowns or as a core material for crowns and three-unit FPDs in the anterior region. Apatite glass ceramics are recommended for veneering. Clinical data exhibited high survival rates for IPS e.max Press onlays (100% after 3 years),<sup>[15]</sup> crowns (96.6% after 3 years),<sup>[16]</sup> monolithic inlay-retained FPDs (100% after 4 years),<sup>[17]</sup> and full crown retained FPDs (93% after 8 years).<sup>[18]</sup> Recently, IPS e.max CAD (Ivoclar Vivadent) has been designed for CAD/CAM processing technology. The milled lithium disilicate block is exposed to a 2-stage crystallization process. Approximately, 40 vol% lithium metasilicate crystals are precipitated during the first stage with their crystal size ranging from 0.2 to 1.0  $\mu\text{m}$ . At this precrystallized state, the CAD/CAM block exhibits a flexural strength of 130–150 MPa, which in turn allows simplified machining and intraoral occlusal adjustment. The final crystallization occurs after milling of the restoration at 850°C in vacuum. The lithium disilicate crystallization occurs after the meta-silicate crystal phase is dissolved completely. The above process also converts the blue shade of the precrystallized block to the selected tooth shade which in turn results in a glass ceramic with a fine grain size of approximately 1.5  $\mu\text{m}$  and a 70% crystal volume incorporated in a glass matrix.<sup>[11]</sup> The flexural strength of CAD/CAM – processed lithium disilicate glass ceramic is 360 MPa. Because of its favorable translucency and shade assortment, the material can be used for fully anatomic (monolithic) restorations with subsequent staining characterization or as a core material with a subsequent coating with veneering ceramics. Its use is recommended for anterior or posterior crowns, implant crowns, inlays, onlays, and veneers. Preliminary clinical results on single crowns revealed high survival rates (100% after 2 years).<sup>[19]</sup>

### DRY-PRESSED AND SINTERED CERAMICS

Densely sintered alumina-based ceramics produced by dry pressing, followed by sintering have been available since the early 1990s. The technique involves computer-aided production of an enlarged die in order to compensate for sintering shrinkage (12–20%). Dry pressing and sintering of a high purity alumina-based core ceramic are then performed done at high-temperature (1550°C). This results in a highly crystalline ceramic with a mean grain size of 4  $\mu\text{m}$  and flexural strength of 601 73 MPa.<sup>[20]</sup> The high-strength core is then veneered with translucent porcelain to obtain adequate esthetics. Clinical results demonstrate an excellent *in vivo* performance at 15 years.<sup>[21–23]</sup>

### SLIP-CAST CERAMICS

In-Ceram Alumina (VITA Zahnfabrik) was the first all-ceramic system available for the single-unit restorations and three-unit anterior bridges with a high-strength ceramic core fabricated with a slip-casting technique. A slurry of densely packed (70–80% wt)  $\text{Al}_2\text{O}_3$  is applied and sintered to a refractory die at 1120°C for 10 h which produces a porous skeleton alumina particles. This is infiltrated with lanthanum glass in a second

firing at 1100°C for 4 h to eliminate porosity and to increase strength. The core is veneered with a feldspathic porcelain.<sup>[24]</sup> In-Ceram Zirconia (VITA Zahnfabrik) is a modified form of original In-Ceram Alumina systems, with the addition of 35% partially stabilized zirconia oxide to the slip composition to strengthen the ceramic. Traditional slip casting technique can be used and the material can be copy-milled from prefabricated, partially sintered blanks and then veneered with feldspathic porcelain. As the core is opaque and lacks translucency, the use of this material for the anterior region becomes problematic.<sup>[25]</sup>

## ZIRCONIA CERAMICS

In the early 1990s, zirconia was introduced to dentistry<sup>[26]</sup> and in recent years, a large number of publications have appeared in the literature. Zirconia is a polymorphic material that occurs in three temperature-dependant phases which are monoclinic (room temperature to 1170°C), tetragonal (1170–2370°C), and cubic (2370°C to melting point).<sup>[26]</sup> Yttrium-oxide ( $Y_2O_3$  3% mol) is added to pure zirconia to stabilize the tetragonal phase at room temperature, enabling a phenomenon called transformation toughening to occur. The partially stabilized crystalline tetragonal zirconia transforms to the more stable monoclinic phase with an associated 3–5% localized expansion.<sup>[27]</sup> This increase in volume counteracts further crack propagation by compression at the tip of the crack.<sup>[28]</sup> High flexural strength (900–1200 MPa)<sup>[29,30]</sup> and high fracture toughness (9–10 MPa.m<sup>1/2</sup>) for zirconia have been reported.<sup>[29]</sup> The most commonly used zirconia are glass-infiltrated zirconia toughened alumina ceramics (In-Ceram, VITA Zahnfabrik) and 3 mol% Y-TZP. Y-TZP has been used for root canal posts, frameworks for posterior teeth, implant-supported crowns, multiunit FPDs, resin-bonded FPDs, implant abutments, and dental implants.

### Zirconia and computer-aided design/computer-aided manufacturing

An assay of CAD/ CAM systems has evolved since F. Duret introduced the concept in 1971.<sup>[31,32]</sup> Most of the available CAD/ CAM systems shape blocks of partially sintered zirconia.<sup>[26]</sup> Milling from partially sintered blocks involves machining enlarged frameworks in a so-called green state. These blocks are then sintered to their full strength, which is accompanied by shrinkage of the milled framework by approximately 25% to the desired dimensions. Examples of these systems are CERCON (Dentsply Friadent, Mannheim, Germany), LAVA (3M ESPE, Seefeld, Germany), Procera (Nobel Biocare, Gothenburg, Sweden), Ekton (Straumann, Basel, Switzerland), and Cerec (Sirona, Bensheim, Germany). The advantage of industrialized block fabrication and reproducible and consistent CAM resulted in increased process reliability, and cost-effectiveness of CAD/CAM-fabricated restorations.<sup>[33]</sup>

### Survival

One of the major drawbacks of zirconia as compared with metal-ceramics is low-temperature degradation and

was first described by Kobayashi *et al.*<sup>[34]</sup> in 1981. At relatively low temperatures (150–400°C), slow tetragonal to monoclinic transformation occurs, initiating at the surface of polycrystalline zirconia and subsequently progressing into bulk of the material.<sup>[26,35]</sup> Transformation of one grain is accompanied by an increase in volume, which causes stress on surrounding grains and microcracking. Water penetration into these cracks then exacerbates the process of surface degradation, and the transformation progresses. The growth of transformation zone results in surface microcracking, grain pullout, and finally surface roughening, which ultimately leads to strength degradation.

### Core/framework fractures

Fractures within the zirconia core ceramic are reported at 7% for single crowns after 2 years at 1–8% for FPDs after 2–5 years. Occlusal overloading caused by bruxism (crown fracture after 1 month<sup>[36]</sup>) or trauma (connector fracture in five-unit FPD after 38 months<sup>[37]</sup>) and insufficient framework thickness of 0.3 mm (crown-abutment fractures in three-unit FPD<sup>[38,39]</sup>) were mentioned as main reasons for zirconia core bulk fractures. Fractographic analyses of clinically failed zirconia crowns showed that radial fractures propagating upward from cementation surface site resulted in bulk fractures.<sup>[40]</sup> Microscopic examinations of failed zirconia-based FPDs revealed that core bulk fractures were most commonly located in the connector area and initiated from the gingival surface, where tensile stresses were the greatest because of occlusal loading.<sup>[41,42]</sup>

### Veneering ceramic cohesive fractures

Cohesive fractures within the veneering ceramic (chipping) are the most frequent reason for failures, irrespective of the applied zirconia veneer system. Veneer fracture rates are reported at 2–9% for single crowns after 2–3 years<sup>[43,44]</sup> and at 3–36% for FPDs after 1–5 years.<sup>[45,46]</sup> Implant-supported zirconia restorations revealed even higher rates at 8% for single crowns after 6 months<sup>[47]</sup> and 53% for FPDs after 1 year.<sup>[48]</sup> Impaired proprioception and rigidity of osseointegrated implants correlated with higher functional impact forces might further exacerbate cohesive veneer fractures. Fractographic analyses of clinically failed veneered zirconia restorations revealed cohesive veneer failures, with cracks originating from the occlusal surface and propagating to core-veneer interface, leaving an intact core.<sup>[41]</sup>

The veneering ceramic material (flexural strength 90–120 MPa) is weak compared with the high-strength core material (900–1200 MPa).<sup>[29,30]</sup> As a result, it is prone to failure at low loads during the masticatory function. However, attempts to improve the microstructure and mechanical properties of veneering ceramics with the development of glass-ceramic ingots for pressing veneering ceramics onto zirconia frameworks did not result in an increased reliability of the veneering ceramic.<sup>[49,50]</sup> Residual stresses in bilayer crowns and FPDs are associated with the possibility of thermal gradients

being developed in these structures during cooling. For zirconia veneer all-ceramic systems, the low thermal conductivity of the zirconia (approximately 3 Wm/K)<sup>[51]</sup> results in the highest temperature difference and therefore, very high residual stresses. In addition, thick layers of veneering ceramics on zirconia cores are highly susceptible to generating high tensile subsurface residual stresses resulting in unstable cracking or chipping.<sup>[52]</sup>

### Framework design

The lack of uniform support of veneering ceramic because of improper framework design has been discussed as a possible reason for chipping fractures. With the introduction of CAD/CAM technologies in dentistry, excessive veneer layer thickness (>2.5 mm) was created because of the uniform layer thickness of the copings for crowns and bar-shaped connectors for FPDs. Improved customized zirconia coping design derived from the conventional porcelain fused to metal technique has been recommended to provide adequate support for the veneering ceramic.<sup>[53]</sup> A dual-scan procedure of die and full contour wax pattern has been merged to fabricate the desired framework. Preliminary *in vitro* studies showed that cohesive fractures within the veneering ceramic could not be avoided with the improved support, but the size of the fractures was significantly decreased<sup>[54,55]</sup> and failure initiation was shifted toward higher loads.<sup>[56]</sup>

### Minimizing core failures

Laboratory technicians and clinicians should follow the precise sequence steps in manufacturing zirconia-based restorations, with the knowledge that zirconia as a framework material is potentially damaged by surface modifications and improper laboratory and clinical handling techniques.<sup>[57]</sup> Grinding or sandblasting of surfaces with high or mild/low-pressure ranges is implicated as a factor in inducing the formation of surface microcracking that could be detrimental to the long-term performance of the restorations and lead to unexpected failures.<sup>[58]</sup> With respect to the highly deleterious effect on zirconia reliability,<sup>[59]</sup> postsintering surface modifications of zirconia frameworks at the dental laboratory or under clinical circumstances should be avoided.

## NEWER CONCEPTS

Manufacturers are now shifting toward the development of monolithic all-ceramic materials instead of bilayer all-ceramic systems to remove the most common failing layer of the system and to avoid inherent residual thermal stresses. Monolithic zirconia ceramic restorations are being researched in high-load bearing areas.<sup>[60]</sup> Separate core and veneer layers than can be joined with nonthermal methods with CAD/CAM technology are evolving at rapid pace. Subtractive CAD/CAM approaches are being now complemented with additive CAD/CAM approach.<sup>[61]</sup>

### Financial support and sponsorship

Nil.

### Conflicts of interest

There are no conflicts of interest.

## REFERENCES

- Denry I, Holloway JA. Ceramics for dental applications: A review. *Materials* 2010;3:351-68.
- Conrad HJ, Seong WJ, Pesun IJ. Current ceramic materials and systems with clinical recommendations: A systematic review. *J Prosthet Dent* 2007;98:389-404.
- Larsson C, Vult von Steyern P, Nilner K. A prospective study of implant-supported full-arch yttria-stabilized tetragonal zirconia polycrystal mandibular fixed dental prostheses: Three-year results. *Int J Prosthodont* 2010;23:364-9.
- Manicone PF, Rossi Iommetti P, Raffaelli L. An overview of zirconia ceramics: Basic properties and clinical applications. *J Dent* 2007;35:819-26.
- Denry I, Rosenstiel SF. Phase transformation in feldspathic dental porcelains. In: Fischman G, editor. *Bioceramics: Materials and Applications*. Westerville, OH: The American Ceramic Society; 1995.
- Guazzato M, Albakry M, Ringer SP, Swain MV. Strength, fracture toughness and microstructure of a selection of all-ceramic materials. Part I. Pressable and alumina glass-infiltrated ceramics. *Dent Mater* 2004;20:441-8.
- Dong JK, Luthy H, Wohlwend A, Schärer P. Heat-pressed ceramics: Technology and strength. *Int J Prosthodont* 1992;5:9-16.
- Krämer N, Taschner M, Lohbauer U, Petschelt A, Frankenberger R. Totally bonded ceramic inlays and onlays after eight years. *J Adhes Dent* 2008;10:307-14.
- Fradeani M, Redemagni M, Corrado M. Porcelain laminate veneers: 6- to 12-year clinical evaluation – A retrospective study. *Int J Periodontics Restorative Dent* 2005;25:9-17.
- Fradeani M, Redemagni M. An 11-year clinical evaluation of leucite-reinforced glass-ceramic crowns: A retrospective study. *Quintessence Int* 2002;33:503-10.
- Höland W, Schweiger M, Watzke R, Peschke A, Kappert H. Ceramics as biomaterials for dental restoration. *Expert Rev Med Devices* 2008;5:729-45.
- Holand W, Apel E, vant Hoen C, Rheinberger V. Studies of crystal phase formation in the early stage crystallization of lithium disilicate glass-ceramics. *J Non Cryst Solids* 2006;352:4041-50.
- Höland W, Schweiger M, Frank M, Rheinberger V. A comparison of the microstructure and properties of the IPS empress 2 and the IPS empress glass-ceramics. *J Biomed Mater Res* 2000;53:297-303.
- Valenti M, Valenti A. Retrospective survival analysis of 261 lithium disilicate crowns in a private general practice. *Quintessence Int* 2009;40:573-9.
- Guess PC, Strub JR, Steinhart N, Wolkewitz M, Stappert CF. All-ceramic partial coverage restorations – Midterm results of a 5-year prospective clinical splitmouth study. *J Dent* 2009;37:627-37.
- Etman MK, Woolford MJ. Three-year clinical evaluation of two ceramic crown systems: A preliminary study. *J Prosthet Dent* 2010;103:80-90.
- Wolfart S, Bohlsen F, Wegner SM, Kern M. A preliminary prospective evaluation of all-ceramic crown-retained and inlay-retained fixed partial dentures. *Int J Prosthodont* 2005;18:497-505.
- Wolfart S, Eschbach S, Scherrer S, Kern M. Clinical outcome of three-unit lithium-disilicate glass-ceramic fixed dental prostheses: Up to 8 years results. *Dent Mater* 2009;25:e63-71.
- Fasbinder DJ, Dennison JB, Heys D, Neiva G. A clinical evaluation of chairside lithium disilicate CAD/CAM crowns: A two-year report. *J Am*

- Dent Assoc 2010;141 Suppl 2:10S-4S.
20. Andersson M, Odén A. A new all-ceramic crown. A dense-sintered, high-purity alumina coping with porcelain. *Acta Odontol Scand* 1993;51:59-64.
  21. Zeng K, Odén A, Rowcliffe D. Flexure tests on dental ceramics. *Int J Prosthodont* 1996;9:434-9.
  22. Hegenbarth EA. Porcelain alumina oxide ceramics: A new way to achieve stability, precision and esthetics in all ceramic restorations. *Quintessence Dent Technol* 1996;19:21-34.
  23. Haag P, Andersson M, von Steyern, Oden VP. A 15 years of clinical experience with proccera alumina. *Appl Osseoint Res* 2004;4:7-12.
  24. Haselton DR, Diaz-Arnold AM, Hillis SL. Clinical assessment of high-strength all-ceramic crowns. *J Prosthet Dent* 2000;83:396-401.
  25. Sundh A, Sjögren G. A comparison of fracture strength of yttrium-oxide-partially-stabilized zirconia ceramic crowns with varying core thickness, shapes and veneer ceramics. *J Oral Rehabil* 2004;31:682-8.
  26. Denry I, Kelly JR. State of the art of zirconia for dental applications. *Dent Mater* 2008;24:299-307.
  27. Calamia JR, Trushkowsky RD, Wolff MS. Esthetic and cosmetic dentistry for modern dental practice: Update 2011. Preface. *Dent Clin North Am* 2011;55:xiii-xiv.
  28. Garvie RC, Hannink RH, Pascoe RT. Ceramic steel? *Nature* 1975;258:703-4.
  29. Christel P, Meunier A, Heller M, Torre JP, Peille CN. Mechanical properties and short-term *in vivo* evaluation of yttrium-oxide-partially-stabilized zirconia. *J Biomed Mater Res* 1989;23:45-61.
  30. Piconi C, Maccauro G. Zirconia as a ceramic biomaterial. *Biomaterials* 1999;20:1-25.
  31. Miyazaki T, Hotta Y, Kunii J, Kuriyama S, Tamaki Y. A review of dental CAD/CAM: Current status and future perspectives from 20 years of experience. *Dent Mater J* 2009;28:44-56.
  32. Rekow ED. Dental CAD/CAM systems: A 20-year success story. *J Am Dent Assoc* 2006;137 (Suppl):5S-6S.
  33. 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.
  34. Kobayashi K, Kuwajima H, Masaki T. Phase change and mechanical properties of ZrO<sub>2</sub>-Y<sub>2</sub>O<sub>3</sub> solid electrolyte after aging. *Solid State Ionics* 1981;3-4:461-87.
  35. Kelly JR, Denry I. Stabilized zirconia as a structural ceramic: An overview. *Dent Mater* 2008;24:289-98.
  36. Cehreli MC, Kökat AM, Akça K. CAD/CAM zirconia vs. slip-cast glass-infiltrated alumina/zirconia all-ceramic crowns: 2-year results of a randomized controlled clinical trial. *J Appl Oral Sci* 2009;17:49-55.
  37. Sailer I, Fehér A, Filser F, Gauckler LJ, Lüthy H, Hämmerle CH. Five-year clinical results of zirconia frameworks for posterior fixed partial dentures. *Int J Prosthodont* 2007;20:383-8.
  38. Beuer F, Edelhoff D, Gernet W, Sorensen JA. Three-year clinical prospective evaluation of zirconia-based posterior fixed dental prostheses (FDPs). *Clin Oral Invest* 2009;13:445-51.
  39. Roediger M, Gersdorff N, Huels A, Rinke S. Prospective evaluation of zirconia posterior fixed partial dentures: Four-year clinical results. *Int J Prosthodont* 2010;23:141-8.
  40. Denry I, Holloway JA. Ceramics for dental applications: A review. *Materials* 2010;3:351-68.
  41. Aboushelib MN, Feilzer AJ, Kleverlaan CJ. Bridging the gap between clinical failure and laboratory fracture strength tests using a fractographic approach. *Dent Mater* 2009;25:383-91.
  42. Taskonak B, Yan J, Mecholsky JJ Jr., Sertgöz A, Koçak A. Fractographic analyses of zirconia-based fixed partial dentures. *Dent Mater* 2008;24:1077-82.
  43. Ortop A, Kihl ML, Carlsson GE. A 3-year retrospective and clinical follow-up study of zirconia single crowns performed in a private practice. *J Dent* 2009;37:731-6.
  44. Groten M, Huttig F. The performance of zirconium dioxide crowns: A clinical follow-up. *Int J Prosthodont* 2010;23:429-31.
  45. Schmitter M, Mussotter K, Rammelsberg P, Stober T, Ohlmann B, Gabbert O. Clinical performance of extended zirconia frameworks for fixed dental prostheses: Two-year results. *J Oral Rehabil* 2009;36:610-5.
  46. Molin MK, Karlsson SL. Five-year clinical prospective evaluation of zirconia-based Denzir 3-unit FPDs. *Int J Prosthodont* 2008;21:223-7.
  47. Nothdurft FP, Pospiech PR. Zirconium dioxide implant abutments for posterior single-tooth replacement: First results. *J Periodontol* 2009;80:2065-72.
  48. 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.
  49. Tsalouchou E, Cattell MJ, Knowles JC, Pittayachawan P, McDonald A. Fatigue and fracture properties of yttria partially stabilized zirconia crown systems. *Dent Mater* 2008;24:308-18.
  50. Guess PC, Zhang Y, Thompson VP. Effect of veneering techniques on damage and reliability of Y-TZP trilayers. *Eur J Esthet Dent* 2009;4:262-76.
  51. Birkby I, Stevens R. Applications of zirconia ceramics. *Key Eng Mater* 1996;122-124:527-52.
  52. Swain MV. Unstable cracking (chipping) of veneering porcelain on all-ceramic dental crowns and fixed partial dentures. *Acta Biomater* 2009;5:1668-77.
  53. Marchack BW, Futatsuki Y, Marchack CB, White SN. Customization of milled zirconia copings for all-ceramic crowns: A clinical report. *J Prosthodont* 2008;99:169-73.
  54. Lorenzoni FC, Martins LM, Silva NR, Coelho PG, Guess PC, Bonfante EA, *et al.* Fatigue life and failure modes of crowns systems with a modified framework design. *J Dent* 2010;38:626-34.
  55. Rosentritt M, Steiger D, Behr M, Handel G, Kolbeck C. Influence of substructure design and spacer settings on the *in vitro* performance of molar zirconia crowns. *J Dent* 2009;37:978-83.
  56. Bonfante EA, Rafferty B, Zavanelli RA, Silva NR, Rekow ED, Thompson VP, *et al.* Thermal/mechanical simulation and laboratory fatigue testing of an alternative yttria tetragonal zirconia polycrystal core-veneer all-ceramic layered crown design. *Eur J Oral Sci* 2010;118:202-9.
  57. Luthardt RG, Holzhüter MS, Rudolph H, Herold V, Walter MH. CAD/CAM-machining effects on Y-TZP zirconia. *Dent Mater* 2004;20:655-62.
  58. Wang H, Aboushelib MN, Feilzer AJ. Strength influencing variables on CAD/CAM zirconia frameworks. *Dent Mater* 2008;24:633-8.
  59. Guess PC, Zhang Y, Kim JW, Rekow ED, Thompson VP. Damage and reliability of Y-TZP after cementation surface treatment. *J Dent Res* 2010;89:592-6.
  60. Zhang Y, Chai H, Lawn BR. Graded structures for all-ceramic restorations. *Dent Mater* 2009;25:892-8.
  61. Silva NR, Bonfante EA, Zavanelli RA, Thompson VP, Ferencz JL, Coelho PG. Reliability of metaloceramic and zirconia-based ceramic crowns. *J Dent Res* 2010;89:1051-6.