Review Article

A new oxide-based high-strength all-ceramic material: An overview

Pilathadka Shriharsha, Vahalová Dagmar, Sukumar Sujith[1], Vosáhlo Tomas
Departments of Prosthodontics and [1]Periodontology, Charles University in Prague, Faculty of Medicine at Hradec Králové, College of Dentistry, Czech Republic

For correspondence
Dr. Pilathadka Shriharsha, Sokolská 581, 500 05 Hradec Králové, Czech Republic. E-mail: drshreeharsha@hotmail.com

Yttrium tetragonal zirconia polycrystals (Y-TZP)-based systems are the recent addition to high-strength all-ceramic systems that are used for crowns and fixed partial dentures. CAD/CAM produced Y-TZP-based systems are being used and in demand in the esthetic zone and in stress bearing regions as well. Furthermore, it is a prospective replacement for the metal-ceramic restorations. This systematic overview covers the results of recent scientific studies and the specific clinical guidelines for its usage.

Key words: All-ceramic restorations, clinical guidelines, fixed partial denture, yttrium tetragonal zirconia polycrystal material

INTRODUCTION

The name “Zirconium” comes from the Arabic word “Zargon,” which means golden in colour. Zirconium (Zr) is a metal with an atomic number of 40. Zirconium dioxide (ZrO_2) was accidentally identified by the German chemist Martin Heinrich Klaproth[1] in 1789, while he was working with certain procedures that involved the heating of some gems. Subsequently, zirconium dioxide was used as a rare pigment for a long time. It was the impure zirconium that was used as the pigment. In the late sixties, the research and development of zirconium as a biomaterial was refined. The use of zirconium as a ceramic biomaterial has been documented. The first recommended use was in the form of ball heads for total hip replacements (THR)[2] in orthopedics. In the early stages of development, many combinations of solid solution (ZrO_2–MgO, ZrO_2–CaO, ZrO_2–Y_2O_3) were tested for biomedical application. However, in subsequent years, research efforts significantly focused on the development of zirconia-yittria ceramics combinations, commonly known as tetragonal zirconia polycrystals (TZPs). The TZPs find its application in space shuttle, automobiles, cutting tools and combustion engines because of its good mechanical strength, fracture toughness and dimensional stability [Tables 1 and 2].

The *in vitro* evaluation of the mutagenic and carcinogenic capacity of high-purity zirconium ceramic confirmed that it did not elicit such effects on the local cellular or systemic reaction to material.[3] In 1990s, zirconium material was used as endodontic posts[4] and as implant abutments.[5,6] This heralded the use of zirconium into dentistry. Due to its excellent physical properties, white colour and superior biocompatibility, it is being evaluated as an alternative framework for full coverage all-ceramic crowns and fixed partial dentures (FPD).

STRUCTURAL PROPERTIES

The transformation-toughened zirconia has unique properties such as high fracture toughness and strength. Zirconium is a polycrystalline ceramic without any glass component. It is a polymorphic material that

Table 1: Physical properties[1]

Property	TZP material
Color	White
Density (gcm^{-3})	>6
Porosity (%)	<0.1
Bending strength (MPa)	900-1200
Compression strength (MPa)	2000
Fracture toughness (K_{IC})	7-10
Coefficient of thermal expansion (K^{-1})	11×10^{-6}
Thermal conductivity (WmK^{-1})	2
Hardness (HV 0.1)	1200

Table 2: Chemical composition of tetragonal zirconia polycrystals material[1]

Chemical composition	Zirconium oxide and yttrium oxide – 3 mol% Hafnium oxide <2% Aluminum oxide + Silicone oxide <1% Total 100%

occurs in three crystallographic forms: monoclinic (M), cubic (C) and tetragonal (T). Pure zirconia at room temperature is monoclinic and stable till 1170°C. Above this temperature, it transforms itself into the tetragonal phase and then further into cubic phase at 2370°C. During cooling, T-M transformation takes place at the temperature range of approximately 100°C below 1070°C. This phase transformation, which takes place during cooling, is associated with volume expansion of approximately 3-4%. This means that components made of pure zirconium oxide would burst due to the volume increase in the grains and tension within.

Later, scientists demonstrated the possibility of the stabilization of C-phase at room temperature by adding a small amount of CaO.[7] The addition of stabilizing oxides, such CaO, MgO, CeO_2 and Y_2O_3 to pure zirconia allows the generation of multiphase materials known as partially stabilized zirconia (PSZ). Gravie *et al*.[8] demonstrated how to make the best use of T-M phase transformation in PSZ, which in turn improves the mechanical and physical properties of the material. The most useful mechanical properties can be obtained when zirconia is in a multiphase form, PSZ. Furthermore, they also observed that the tetragonal (T) phase of PSZ is in a metastable state at room temperature. The state is metastable because the transformation from T phase to M phase can be induced by external influences such as tension and temperature. When tensile stresses act on the crack tip in PSZ, it induces the transformation of metastable T phase to M phase. This transformation is associated with a local increase of 3-5% in volume. This increase in volume results in the generation of localized compressive stresses around and at the crack tip, thereby squeezing the crack. This physical property is known as "transformation toughening."

To obtain a metastable tetragonal structure at room temperature (Y_2O_3 (3 mol%) doped with tetragonal ZrO_2), the ceramic grain size is also very critical and it must be less than 0.8 µm. A critical grain size is linked to the yttrium concentration; above which spontaneous T-M transformation of the grains take place, whereas on the other hand this transformation would be inhibited in an overly fine-grained structure.[1]

Design and manufacture of Y-TZP-based restorations

Zirconium dioxide ceramics are used in dentistry as framework materials for the fabrication of crowns and posterior FPDs. The frameworks are primarily fabricated by the help of a CAD/CAM system by means of the milling of a ZrO_2 block. The zirconium blocks are manufactured under well-controlled industrial conditions.

Y-TZP-based zirconium frameworks for crowns or FPDs are designed by advanced Computer assisted design (CAD) and special software provided by the manufacturers. This designing software is unique and differs among manufacturers. Cercon® smart ceramic system (DeguDent Gmbh, Germany) utilizes conventional waxing method for designing the infrastructure for crowns and bridges with specific thickness. A special laser scanner scans the wax pattern and the data are transferred into the computer-aided manufacturing (CAM) unit. This data is then utilized for milling the framework from partially sintered Y-TZP blanks. The LAVA®[9] (3M ESPE Dental Products, St. Paul, MN) and DCM-Precident® (Direct Ceramic Machining Process, ETH Zurich, Switzerland) systems use different types of CAD software with different designing options and features. Table 3 presents the type of the blocks used by the different systems and with commercial examples.

When the partially sintered blanks are used, the sintering shrinkage of 20-25% has to be compensated by increasing the framework size to attain good marginal fit.[10,11] The system that uses fully sintered blank (HIP) takes longer time for milling due to the increased hardness of blank. Studies show superior marginal fit by the virtue of not having sintering shrinkage.[10] The CAD/CAM system use contact scanning or laser to record the details of the prepared tooth model. Manufacturers who uses contact scanning, claim that digitization of details of prepared tooth are not as accurate as non-contact scanning by laser. However, Ann Persson *et al.*[12] found that the reproducibility and accuracy of non-contact scanning data was similar to that of contact scanning with a mean difference of 10 µm. The precision fit of the prosthetic restoration is dependent on multiple factors such as

Table 3: The commercial examples of differnt types of CAD/CAM-based fabrication of zirconum oxide substructure[9,13]

Type of ZrO² blocks	Milling procedure	Advantages	Commercial examples
Green stage	Dry carbide burs	Less time for milling Less flaws Post-milling sintering at 1500°C	Cercon base, Cercon (Degudent, Germany); Lava Frame, Lava (3M ESPE); Zirkon Zahn, Steger (Brunneck, Italy)
Presintered	Carbide burs under coolant.	Less time for milling Less flaws Post-milling sintering at 1500°C	In-Ceram YZ Cubes, Cerec InLab (Sirona, Germany); ZS-Blanks, Everest (KaVo, Germany); Precident DCS (DCS, Switzerland)
Completely sintered	Diamond burs under coolant.	More time for milling Expensive No sintering shrinkage	Z-Blanks, Everest (KaVo, Germany); Hint-ELs Zirkon TZP-HIP; DigiDent (Girrbach, Germany); DC-Zirkon, Precident DCS (DCS, Switzerland)

manufacturing process, tooth preparation, impression and fabrication of dental cast.

The commercially available zirconium oxide frameworks were primarily fabricated by the help of CAD/CAM-controlled milling from industrially fabricated zirconium oxide blanks. The stages of sintering can be presintered, partially sintered and fully sintered. The types of the blanks used decide the method of milling to be employed during fabrication [Table 3]

CLINICAL GUIDELINES

Appropriate measures have to be taken while selecting the patient in addition to the detailed intraoral examination that forms an integral part of diagnosis. The criteria for patient selection include interocclusal space, parafunctional habits and mobility of the tooth. The assessment of the abovementioned criteria mentioned is of utmost importance for clinical success. The strength of Y-TZP is approximately 900-1200 MPa and flexural strength (K_{IC} value) ranges between 8 to 12 MPa/m$^{1/2}$.[14,15] In case of FPDs, the minimum clinical height of the prospective abutment (interproximal papilla to the marginal ridge) should be 4 mm[15] and the total surface area of connecter should be 7-16 mm^2.[15] Clinically, these measurements can be registered using a periodontal probe. Fractographic study and *in vivo* studies demonstrated that the modes of failure of all-ceramic FPDs are the vertical fracture of connector at the pontic region.[16] In a clinical situation where there is an increased mobility of abutment teeth, a high risk of FPD fracture is observed.

Contraindication

- Very short clinical crown that does not permit the adequate height of connector (occlusal-gingival and mesio-distal)
- In Class II Division II malocclusion patients, due to deep bite, there will be insufficient space for the labio-lingual connector width.
- As cantilever pontic
- Bruxism
- Participation in extreme sports
- Clinical situation wherein biomechanics is compromised (i.e., not satisfying the Ante's law and the presence of Bruxism)

Y-TZP based frameworks are milled from white- and ivory-coloured blanks. The white color of the framework can be a clinical limitation for its use in the esthetic zone. To overcome this problem, systems like LAVA® (3M ESPE) have introduced a new technique of staining the framework. The framework for crown and bridges can be stained with one of the seven shades of Vita®-Lumin shade guide before sintering. This staining allows the achievement of the final shade from the intaglio surface to the external surface of the veneering ceramic. LAVA® system is comparatively more translucent than other contemporary systems.[15] Due to the possibility of shading the framework in an esthetically compromised surface, we can even avoid layering with the veneering ceramic. The ability to control the shade of the core can also eliminate the need to veneer the lingual and gingival surfaces of the connector area due to limited interocclusal clearance. However, systems such as Cercon® and DCS -Precident® use white-colored frameworks. Owing to this, the latter two systems are difficult to use in an esthetically demanding situation.

Tooth preparation guidelines are comparable to metal-ceramic crown and bridge preparations. It is strongly advisable to follow the manufacturers' recommendations and to use the advised preparation kit. The axial reduction should be approximately 1.2-1.5 mm, and occlusal reduction should be 1.5-2.0 mm. The occlusal reduction should not be anatomical. The axial taper of crown preparation should be of 5-6°. All the sharp edges of the crown need to be smoothened. The gingival finish line should be distinct, uniform and can be at the gingival margin or placed 0.5 mm subgingivally. The recommended cervical finish line is 0.8 or 1.2 mm deep chamfer or shoulder with a rounded internal angle. There can be some variations between different systems for the amount of axial tooth reduction, for example, the minimum thickness for a Lava®-framework is 0.5 mm, whereas Cercon® smart ceramics suggest a reduction of 1 mm and CICERO®, 0.7-1.2 mm. Recent publications recommend a chamfer finishing line for the crowns and a shoulder with rounded internal angle design for the favourable distribution of occlusal stresses to abutment teeth during the function for the bridges.[17]

Full coverage Y-TZP-based restorations can be cemented using conventional cements. It can also be bonded using adhesive cementation. Some studies do not strongly recommend the use of adhesive cementation alone.[18] However, adhesive bonding is suggested as an alternative in some clinical situations such as compromised retention and short clinical crown length of an abutment. Kern *et al.*[19] showed in his study that by using airborne particle abrasion with 110 µm of Al_2O_3 at 2.5 bars pressure on the fitting surface of crown or FPD, combined with phosphate-modified resin cement Panavia 21 (Kurary, Tokyo, Japan), achieved highest bond between zirconium and tooth.

CLINICAL STUDY RESULTS

Extensive laboratory studies have confirmed the strength superiority of zirconium-based restorations. The availability of long-term prospective clinical study results is limited for these new materials. Recently, the interim results of a long-term prospective clinical study of one of the Y-TZP materials LAVA® (3M ESPE) was reported.[20] This study consisted of 16 three-unit posterior FPDs and at the end of 36 months good clinical performance was noted in terms of marginal integrity, marginal discolouration and secondary decay. However, the minor chipping of veneer porcelain was observed and it did not require any correction. In another ongoing study of DC-Zirkon® (DCS® Precident system) of 18 patients, a total of 20 FPDs (3-5 units) at the end of a 3-year period showed 100% success rate in the anterior and posterior teeth.[16] However, similar chipping fractures of veneer porcelain were observed. The long-term report of other ongoing studies will confirm the final clinical usage.

CONCLUSION

A combination of superior physical properties, biocompatibility and excellent esthetics make TZP popular among the contemporary all-ceramic materials.[21] The method of production of this material is simplified by utilizing the high technology CAD-CAM technique. This also completely eliminates the conventional laboratory procedures. The CAD-CAM method for design and production impart consistent quality, superior marginal fit and can satisfy the critical esthetic needs of the patients. This system scores over other systems because it does not require very complicated clinical procedures. Extensive *in vitro* and *in vivo* studies have confirmed high fracture resistance and its use in the stress-bearing areas. The 5-year clinical follow-up studies that are in progress have shown a positive result at the end of the first year.

REFERENCES

1. Piconi C, Maccauro G. Zirconia as ceramic biomaterial. Biomaterials 1999;20:1-25.
2. Piconi C, Burger W, Richter HG, Cittadini A, Maccauro G, Covacci V, *et al.* Y-TZP ceramics for artificial joint replacements. Biomaterials 1998;19:1489-94.
3. Covacci V, Bruzzese N, Maccauro G, Andreassi C, Ricci GA, Piconi C, *et al. In vitro* evaluation of mutogenic and carcinogenic power of high purity zirconia ceramic. Biomaterials 1999;20:371-6.
4. Koutayas OS, Kern M. All-ceramic posts and cores: The state of the art. Quintessence Int 1999;30:383-92.
5. Brodbeck U. The ZiReal post: A new ceramic implant abutment. J Esthet Restor Dent 2003;15:10-23.
6. Boudrias P, Shoghikian E, Morin E, Hutnik P. Esthetic option for the Implant supported single-tooth restoration: Treatment sequence with a ceramic abutment. J Can Dent Assoc 2001;67:508-14.
7. 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.
8. Garvie RC, Hannink RH, Pascoe RT. Ceramic steel? Nature 1975;258:703-4.
9. Piwowarczyk A, Ottel P, Lauer HC, Kuretzky T. A clinical report and overview of scientific studies and clinical procedures conducted on the 3M ESPE Lava™ all-ceramic system. J Prosthodont 2005;14:39-45.
10. Ariko K. Evaluation of marginal fitness of tetragonial zirconia polycrystal all-ceramic restorations. Kokubyo Gakkai Zasshi 2003;70:114-23.
11. 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;113:174-9.
12. Persson A, Anderson M, Oden A, Englund GS. A three-dimensional evaluation of a scanner and touch-probe scanner. J Prosthet Dent 2006;95:194-200.
13. Witkowski S. CAD-CAM in dental technology. Quintessence Dent Technol 2005;28:1-16.
14. Guazzato M, Proos K, Quach L, Swain MV. Strength, reliability and mode of fracture of bilayered porcelain/zirconia (Y-TZP) dental ceramics. Biomaterials 2004;25:5045-52.
15. Raigrodski AJ. Contemporary materials and technologies for all ceramic fixed partial dentures: A review of the literature. J Prosthet Dent 2004;92:557-62.
16. Kelly JR, Tesk JA, Sorensen JA. Failure of all-ceramic fixed partial dentures *in vitro* and *in vivo*: Analysis and modelling. J Dent Res 1995;74:1253-8.
17. Vult von Steyern P. All-ceramic fixed partial dentures: Studies on aluminum oxide and zirconium dioxide based ceramic systems. Swed Dent J Suppl 2005;173:1-69.
18. Ernst Priv CP, Cohnen U, Tender E, Willershausen B. *In vitro* retentive strength of zirconium oxide ceramic crowns using deferent luting agents. J Prosthet Dent 2005;93:551-8.
19. Kern M, Wegner SM. Bonding to zirconia ceramic: adhesion methods and their durability. Dent Mater 1998;14:64-71.
20. 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;96:237-44.
21. Raigrodski AJ. Contemporary all-ceramic fixed partial dentures: A review. Dent Clin North Am 2004;48:531-44.

Source of Support: Nil, **Conflict of Interest:** None declared.