

Literature Review

Y-TZP Ceramics: Key Concepts for Clinical Application

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Clinical Relevance

The description of the chief characteristics of Y-TZP ceramics provides a background for its clinical application. Both the improved mechanical properties and the lower bonding ability of Y-TZP materials are frequently suggested by the literature. Nevertheless, the combination of air abrasion with aluminum oxide particles (silanated or not), followed by materials containing special reactive monomers, seems to be a potential adhesion mechanism.

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SUMMARY

Compared to conventional ceramic systems, Yttrium-stabilized tetragonal zirconia (Y-TZP) ceramics have some superior mechanical properties, ensuring a broad application in dentistry. The current study aimed to present relevant information about Y-TZP ceramics gathered from peer-reviewed papers. A search of the English language peer-reviewed literature was conducted using the PubMed database between 1998 and 2008. Articles that did not focus exclusively on the clinical application of Y-TZP ceramic restorations were excluded from further evaluation. Selected papers describe the chief characteristics of zirconia ceramics and important clinical features, especially those related to cementation procedures. The literature shows that, although new substances and equipment for the surface preparation of zirconia ceramics are in development, the most promising luting protocol seems to be the use of air abrasion with aluminum oxide particles (silanated or not), fol-

lowed by the application of resin cements or surface primers containing special reactive monomers. However, because zirconia ceramics have only recently been developed for dental applications, there is not enough clinical evidence to support any definitive cementation protocol.

INTRODUCTION

A progressive improvement in the mechanical properties of dental ceramics has led to an increase in metal-free restorations.¹⁻³ The zirconia systems currently available for use in dentistry include ceramics with a zirconium dioxide content higher than 90%, which is the yttrium-stabilized tetragonal zirconia (Y-TZP), and glass-infiltrated ceramics with 35% partially-stabilized zirconia. Because of the superior mechanical properties of Y-TZP ceramics, these materials have a wide range of clinical applications, from implant abutments and single-tooth restorations to fixed partial dentures (FPDs) involving several elements.²⁻⁷

In contrast to conventional dental ceramics, Y-TZP is composed of many small particles without any glassy phase at the crystallite border.⁵ The absence of a silica and glassy phase impairs the effectiveness of conventional adhesive luting procedures, which include etching ceramic surfaces with hydrofluoric acid and applying silanes prior to the use of a resin cement.^{1,3,6-10} Recent studies have suggested specific luting techniques for Y-TZP ceramics. These include surface treatments and the use of materials with a chemical affinity for zirconium dioxide.^{1-4,6-12}

Although Y-TZP has been used as a ceramic biomaterial in medical applications since the late 1960s, its use in dentistry is relatively recent.^{11,13} For this reason, it is not surprising that dentists question the clinical applications and cementation of this type of ceramic. The current study aimed to collect information about Y-TZP ceramics in order to describe their chief structural characteristics, clinical features, manufacturing procedures and specificities related to the luting procedure.

DENTAL CERAMICS

As a result of the good properties of dental ceramics, such as esthetics, hardness, resistance against compression, chemical resistance and biocompatibility, a significant effort has been made to improve their weak points, such as brittleness and low tensile strength.¹⁴ There are different ways to strengthen ceramic systems in order to minimize flaw propagation through the material, the most important ones being dispersion strengthening and transformation toughening.¹⁴ Dispersion strengthening is based on the addition of a disperse phase of a different material that is capable of hindering a crack from propagating. When tiny crystals of a tough material are homogeneously distributed

throughout the glass matrix, the ceramic structure is toughened and strengthened, because the crack cannot propagate through the crystals as easily as it does through the glass.¹⁴ Dental ceramics can be reinforced with a wide variety of crystalline disperse phases, such as alumina, leucite, lithium disilicate and zirconia. Nevertheless, toughening depends on the crystal type, its size and volume fraction, the interparticle space and the relationship between the thermal expansions of glass and the crystalline phases.¹⁴

The other method of ceramic reinforcement is based on the use of a material that undergoes microstructural changes when submitted to stress. This mechanism is known as stress-induced transformation toughening.¹³⁻¹⁶ The crystalline structure of the zirconium dioxide experiences a transformation from a tetragonal (T) to a monoclinic (M) phase at the tips of cracks. The stress associated with expansion due to the phase transformation acts in opposition to the stress that promotes the propagation of the crack. The energy associated with crack propagation is dissipated for the T-M transformation and for overcoming the compression stresses caused by volume expansion.¹³⁻¹⁶ Therefore, highly intense tension will be necessary for the fracture to continue propagating.¹⁴ The development of materials with stress-induced transformation toughening is considered one of the most remarkable innovations in the study of ceramics.¹⁵

Y-TZP CERAMICS

Zirconia is a name given to zirconium dioxide (ZrO_2). Zirconia is a polymorphic material, thus, it can exhibit more than one crystalline structure, depending on the temperature and pressure conditions. Polymorphic transformations are followed by changes in density and other physical properties of the material. Pure zirconia is monoclinic (M) at room temperature. This phase is stable up to 1,170°C. Under higher temperatures, it will transform into a tetragonal (T), and later into a cubic phase (C) at 2,370°C. The phase transformation that occurs during cooling to room temperature is associated with vast volumetric expansion. Stresses generated by the expansion generate cracks in pure zirconia ceramics, which, after being sintered between 1,500°C and 1,700°C, can break into pieces at room temperature. This vast volumetric expansion precludes the use of pure zirconia in ceramic systems.¹³⁻¹⁴

The addition of stabilizing oxides to pure zirconia allows for the generation of multiphase materials. In the early stages of the development of zirconia ceramics, several dopants were tested, including CaO, MgO, CeO_2 and Y_2O_3 . Most research on zirconia ceramics for dental applications is focused on yttrium-doped ceramics.¹³ The addition of 3%–6% weight of Y_2O_3 can prevent polymorphic transformation during heating and cooling. Through the ZrO_2 - Y_2O_3 system, one can obtain a

Table 1: Commercial Brands of Zirconia Ceramics, Manufacturers, Classification and Composition		
Commercial Brand (manufacturer)	Manufacturing	Composition*
Cercon Smart Ceramics (DeguDent, Hanau, Germany)	CAM of partially sintered Y-TZP blanks	5% Y ₂ O ₃ TZP
LAVA All-Ceramic System (3M ESPE, Seefeld, Germany)	CAM of partially sintered Y-TZP blanks	3% Y ₂ O ₃ TZP
Procera Zirconia (Nobel Biocare, Göteborg, Sweden)	CAM of partially sintered Y-TZP blanks	4.5-5.4% Y ₂ O ₃ TZP
DCZirkon (DCS Dental AG, Allschwil, Switzerland)	CAM of fully sintered blanks	5% Y ₂ O ₃ TZP
Vita In-Ceram YZ Cubes (Vita Zahnfabrik, Bad Säckingen, Germany)	CAM of partially sintered Y-TZP blanks	5% Y ₂ O ₃ TZP
Vita In-Ceram Zirconia (Vita Zahnfabrik)	Glass-infiltration processing	33% t-ZrO ₂ (Ce-stabilized), 67% Al ₂ O ₃
*According to the information provided by the manufacturers.		

ceramic material consisting of the tetragonal phase only, which is known as yttrium tetragonal zirconia polycrystals (Y-TZP).¹³⁻¹⁴ There is another type of zirconia material available, glass-infiltrated zirconia ceramic. This system presents a high crystal content of aluminum and zirconium oxide and a limited vitreous phase (approximately 20wt%). Commercial brands, manufacturers, the manufacturing process and the composition of some current zirconia ceramic systems are presented in Table 1.

Stress-induced transformation toughening is a unique characteristic of Y-TZP ceramics that gives them superior mechanical properties compared with other ceramics^{12,17} and can explain why this material is referred to as a “ceramic steel” by some authors.^{14,17} The formation of compressive layers on their surface is a consequence of the toughening mechanism induced by external stresses or temperature changes.^{12,17} These layers can result in increased hardness and can have an important role in the improvement of the mechanical properties of Y-TZP materials. On the other hand, a continuing progression of phase transformation might initiate surface flaws, followed by the ejection of grains, resulting in catastrophic effects on mechanical properties, making the material more vulnerable to aging.^{13,16}

Mechanical properties can influence the clinical behavior of metal-free restorations.¹⁸ Studies have shown that Y-TZP ceramics present superior mechanical properties compared with other dental ceramics—even higher than glassy-infiltrated zirconia ceramics.¹⁸ The flexural resistance of Y-TZP ceramics can reach values from 700 to 1200 MPa.^{12,18-19} These values exceed the maximal occlusal loads during normal chewing.¹⁹ Y-TZP materials might also exhibit a fracture resistance of more than 2,000 N, which is almost twice the value

of alumina-based materials and almost three times the value of lithium disilicate-based ceramics.²⁰

CLINICAL APPLICATION AND THE MANUFACTURE OF Y-TZP CERAMICS

The clinical application of indirect restorations made of zirconia ceramics include FPDs supported by teeth or implants. Because of its higher mechanical properties, this material can be used in several clinical situations, anywhere from a single-unit restoration to FPDs with multiple elements in the anterior or posterior region of the oral cavity.²¹⁻²² Although some manufacturers indicate that zirconia ceramics allow for the fabrication of a prosthesis involving the full arch, FPDs with a maximum of five units seem to be more reliable.²³⁻²⁴ This material can also be used for posts and cores or implant abutments in prosthetic dentistry.⁶

Y-TZP ceramics can be colored to simulate tooth structure; however, they are highly opaque.²³ This radiopacity can be very useful for monitoring their marginal adaptation through radiographic analysis, especially when intrasulcular and proximal preparations are performed.²³ On the other hand, opacity might limit the esthetic outcome of zirconia restorations compared with those made of conventional dental ceramics.

Frameworks in Y-TZP are produced using a CAD/CAM system (computer-aided design/manufacturing) that involve both clinical and laboratory steps. Preparations must follow the free gingival margin; incisal/occlusal reduction should be at least 1.5 mm and axial reduction should be a maximum of 1.0 mm. Excessively tapered preparations should be avoided.^{4,23} Chamfer or rounded-shoulder preparations are recommended, because they increase material thickness at the restoration margins.²³ Knife-edge preparations

might also be appropriate, since the fracture load required for Y-TZP copings with this type of preparation was greater than that required for chamfer preparations, regardless of coping thickness.²⁵ The diameter of the connector might vary according to the length of the FPD.^{24,26} It was suggested that connector diameters of 4.0 mm could be sufficient for FPDs that replace molars and for those involving four or more units. Greater diameters (>4.0 mm) may be necessary if excessive forces are expected, as in patients with a deep overbite, bruxism or those who have a history of fractured reconstructions. For shorter FPDs and anterior ones, smaller connectors might be adequate.²⁶

After conventional impression and die-fabricating procedures, the tooth preparation is scanned following the CAD/CAM procedure, or the restoration is waxed up and further scanned for the CAM procedure.²⁷ There are two major techniques for manufacturing Y-TZP frameworks. In the first technique, partially-sintered zirconia blocks are milled according to the shape of the restoration but in a higher dimension to compensate for the linear shrinkage that occurs after sintering. Then, the ceramic is sintered and the framework shrinks to the final dimension.^{22,27} Pre-sintered zirconia is easier to shape but must be sintered after milling to achieve maximum strength.²⁸ In the second method, restorations of the final dimension are milled from fully-sintered zirconia blocks. No further heat treatment, with associated dimensional change, is required.²⁸ In both techniques, the frameworks are veneered with a porcelain to recreate the natural appearance of the tooth.²⁹

The veneer material plays an important role in the mechanical behavior of all-ceramic FPDs, since it affects stress distribution on the FPDs and also contains critical flaws from which crack propagation can initiate.³⁰ The performance of the complex Y-TZP framework-veneer porcelain has been investigated.³⁰⁻³¹ In a study testing the fast fracture behavior of veneer-framework composites for all-ceramic FPDs, the authors noted that cracks originating on the veneer layer deflected at the veneer-Y-TZP framework interface, resulting in the delamination of the veneer layer before complete fracture of the sample at higher stress levels. The same fracture mode was observed in other studies.³¹ Although this finding resulted from *in vitro* conditions, which are far different from a clinical situation, it can be clinically relevant, because it indicates that tougher framework materials are able to stop cracks originating on the weaker veneer layer, thus avoiding catastrophic failure of the prosthesis.³⁰

The mechanical properties of Y-TZP ceramics depend not only on the microstructure of the material, but also on the manufacturing process of the frameworks/restorations.^{13,19,32} Studies have investigated the effect of milling, thermal alterations, and finishing and polish-

ing procedures on the performance of zirconia ceramics. Milling can result in contradictory effects.³² It can induce compressive layers on the surface, and those layers can improve the mechanical properties of the material. On the other hand, milling can also produce flaws that exceed the thickness of the compression layer, depending on the percentage of the T-M phase transformation, milling severity and temperature.^{12,32}

The consequences of different milling parameters (speed of milling and wear depth) on the characteristics of a Y-TZP ceramic have been investigated and the results showed that they significantly affect the strength and reliability of the material.⁵ The authors concluded that the methods for fabrication of zirconia structures still need to be improved in order for restorations to reliably fulfill their purposes. In addition, a major factor related to milling is the size of the grain; the bigger the size of the abrasive, the thicker the superficial flaw.⁵

Temperature can also adversely affect the properties of Y-TZP frameworks. Heat generated during application of the veneering porcelain (maximum temperature of 930°C) can induce the reverse phase transformation M-T, thus diminishing the content of the monoclinic phase, preventing the generation of compressive layers and, consequently, affecting the properties of the material.³² In addition, zirconia ceramics can suffer a process known as low temperature degradation (LTD).¹⁶ This aging occurs through the slow and continuous phase transformation in the presence of water or humidity.¹⁶ A previous study found that treatments at low temperatures (250°C) and under humidity did not diminish the flexural resistance of a Y-TZP material.¹⁹ Nevertheless, chemical composition analysis through energy dispersive spectroscopy (EDS) revealed that the yttrium concentration reduced significantly after thermal aging, from a weight of 6.76% to 4.83%. According to the authors, reducing the yttrium percentage might affect the material's stability, thus making the ceramic susceptible to progressive phase transformations.¹⁹

Air abrasion with aluminum oxide particles is routinely performed to remove layers of contaminants, thus increasing micromechanical retention between the resin cement and the restoration.^{2,33} Usually, air abrasion units use aluminum oxide particles with sizes ranging from 25 µm to 250 µm. These particles may or may not be silica-coated (tribochemical treatment).³⁴ The effect of air abrasion on the mechanical properties of zirconia has been repeatedly discussed in the literature, and both positive and negative results have been described.^{12,19,34}

Some authors have stated that air abrasion increases the flexural resistance of zirconia ceramics, because it induces T-M phase transformations, creating compressive layers on the surface.^{12,19,34} Apparently, the depth of

the surface flaws induced by air abrasion do not exceed the thickness of the compressive layers, justifying the improved properties of air-abraded surfaces.¹⁹ When the effects of air abrasion and milling with fine-grained diamond instruments (20 μm –40 μm) were compared with the use of coarse diamond burs (125 μm –150 μm), it was observed that less severe protocols reduced surface roughness and provided the formation of compressive layers on the surface. Conversely, coarse diamond burs reduced the flexural strength and reliability of Y-TZP ceramics.³⁴ In a different study, air abrasion and coarse diamond burs also presented opposite effects on the flexural resistance of a zirconia ceramic.¹² The authors of that study added that, during milling with the diamond bur, a vast amount of material was removed and sparks were commonly observed despite the use of constant water spray, indicating that both stress and temperature were high during the operation.¹²

Tribochemical coating seems to be less effective for zirconia ceramics than for glass-infiltrated ceramics.^{4,8} In this technique, air pressure impregnates the ceramic with silica particles, and further silane application renders the impregnated surface chemically reactive to the resin cement.³³ However, siloxane bonds (including silica, silane and resin cement) are formed only if the surface presents oxygen and silica, because both molecules present linking sites between silane and the ceramic.³⁵ Y-TZP ceramics present greater hardness compared with systems with a glassy structure, which prevents the impregnation of silica onto the surface.³⁵ For this reason, silane agents do not bond adequately to zirconia ceramics.⁸ Although some studies have demonstrated good results with tribochemical treatment,^{9,36} the question might be posed whether the improved bonding was caused by the siloxane bond or micromechanical retention, and this fact should be investigated in further studies.

According to some other studies, surface treatments, such as air abrasion, might increase ceramic degradation over time. It was demonstrated that the strength of air abraded Y-TZP ceramic decreases significantly when specimens are submitted to fatigue. This might be indicative of the presence of surface flaws, which increase with cyclic loading, and they can negatively affect the material's properties.³⁷ Any further grinding or abrasion performed during the luting procedure might exacerbate superficial flaws created by air abrasion, resulting in fracture propagation.³⁷

Despite the possible negative outcomes of surface treatments on the mechanical properties of Y-TZP materials, the application of resin cements to untreated surfaces apparently result in low bond strength, which is unable to resist water storage.² This fact might indicate that some surface alteration is fundamental in order to obtain a durable bond to zirconia.² Additionally, in a long-term clinical study with alumina and zirconia

FPDs, the authors noted that fractures only occurred at untreated sites, never at air abraded surfaces.³⁸

Other techniques for the superficial treatment of zirconia ceramics have been described; these are plasma spraying and fusing glass pearls to the zirconia surface.³ Both treatments improved the bond strength of resin cements to the surface. Nevertheless, they were not compared with conventional methods of surface treatments for Y-TZP ceramics, such as air abrasion and tribochemical coating.³ The plasma is a partially-ionized gas containing electrons, atoms and neutral species. Covalent bond formation following plasma application might be an explanation for the higher bond strengths, although this mechanism has not been fully elucidated. On the other hand, fusing glass pearls to zirconia ceramics increases the surface roughness, improving the retention of the resin cement to the surface.³

BONDING TO Y-TZP CERAMICS

The longevity of an indirect restoration is closely related to the integrity of the cement at the margin.³³ Although the use of zirconia ceramics for dental applications is ongoing, the best method to promote a durable bond between the ceramic and tooth structure is still unknown.⁸ The only consensus found in the literature is that hydrofluoric acid etching and common silane agents are not effective for zirconia ceramics.⁸⁻¹⁰

A great diversity of materials for luting metal-free restorations is commercially available. These include zinc phosphate cements, conventional and resin-modified glass ionomer cements, resin cements and self-adhesive resin cements.³⁹ However, resin cements possess some advantages compared with the other classes of materials, since they have lower solubility and better esthetic characteristics.^{1,11,39-40} In addition, the adhesive bond between the resin cement and ceramic might increase the restoration's resistance during occlusal loads.^{1,39-40}

The shear bond strength of 11 different types of cements to a Y-TZP ceramic was evaluated.³⁹ The results indicated that zinc phosphate and conventional and resin-modified glass ionomer cements were not able to form a durable bond to zirconia.³⁹ In another study, the authors stated that the bond strength of glass-ionomer cements and that of a conventional Bis-GMA-based resin-composite to zirconia ceramics is significantly lower, especially after thermal aging.¹¹

There is some evidence that demonstrates that a better bond to Y-TZP ceramics is obtained using resin cements with phosphate ester monomers, such as the MDP monomer.^{2,7-11} The phosphate ester group might chemically bond to metal oxides, such as zirconium dioxide.^{2,10-11} Wolfart and others² evaluated the durability of the bond with two resin cements (MDP-based and

Bis-GMA-based) to a zirconia ceramic. The MDP-based material presented higher bond strength to zirconia surfaces air abraded with alumina particles and this bond survived 150 days of water storage.² Other studies also stated that resin cements with phosphate ester groups increase the bond strength of air abraded and tribochemically-coated surfaces.^{8-9,11}

Other monomers present in resin cements might also have a chemical affinity for metal oxides.^{11,36,39} For example, the anhydride group present in 4-META monomer and the phosphoric methacrylate ester can also chemically bond to zirconia ceramics.^{11,36} It was observed that the bond strength of a polymethylmethacrylate (PMMA) resin cement containing 4-META was initially high; however, this bond was not strong enough to resist thermal aging.¹¹ Water absorption by the PMMA during thermal cycling may have weakened the chemical bond.¹¹ On the other hand, the use of a self-adhesive cement containing phosphoric methacrylate ester resulted in bond strengths to zirconia similar to that of MDP-based resin cements after 14 days of thermal cycling and water storage.³⁹ In another study, this cement provided similar coping retention compared to a MDP-based resin cement and a resin-modified glass ionomer cement.⁴¹ The mean coping removal stresses for the axial surface ranged from 6.7 MPa to 8.5 MPa, which is similar to the range of removal stress observed for gold castings when using zinc phosphate and glass ionomer cements. The authors concluded that the three cements tested are capable of retaining zirconium oxide crowns successfully, requiring no additional internal surface treatment other than airborne-particle abrasion with 50- μ m aluminum oxide followed by appropriate cleaning of the crown prior to cementation.⁴¹

A previous study⁴² indicated that the application of an MDP-containing bonding/silane coupling agent is the key factor for a reliable resin bond to Y-TZP ceramics and is not influenced by the resin luting agent used. Currently, in the dental market, priming agents that contain special adhesive monomers are available to improve adhesive bonding to metal alloys. In addition to MDP, these substances contain other monomers, such as VBATDT (6-(4-vinylbenzyl-n-propyl)amino-1,3,5-triazine-2,4-dithione), MEPS (thiophosphoric methacrylate) and MTU-6 (6-methacryloyloxyhexyl-2-thiouracil-5-carboxylate). Yoshida and others¹⁰ stated that the bond strength between resin cement and zirconia increased significantly when surfaces were coated with an MDP-based metal primer. However, this bond could not resist thermal aging. The results of this study also showed that a mixture of MDP-based metal primer with a zirconate agent (2,2-di[allyloxymethyl] butyl trimethacryloyl zirconate) strengthened the bond between resin cement and zirconia ceramic. This mixture might be a clinically effective way to improve

bonding to these ceramics and should be further investigated.¹⁰

CONCLUSIONS

Based on the scientific evidence gathered in this literature review, the following conclusions can be drawn:

- The methods for manufacturing Y-TZP frameworks and treating surfaces that were previously luted can affect the mechanical properties of zirconia ceramics. Nevertheless, the clinical implication of such modifications has not been determined.
- Air abrasion with aluminum oxide particles (silanated or not) is the surface treatment most frequently indicated for improving the bond between resin cements and Y-TZP ceramics. Although studies have indicated that some surface treatments may lower the mechanical properties of Y-TZP materials, this effect might depend on the aggressiveness of the abrasive technique.
- The use of special functional monomers that can chemically bond to zirconium dioxide appear to improve the quality of the bond between resin cement and ceramic. Currently, these monomers are found in both resin cements and metal primer solutions.
- Although several scientific studies are currently available, clinical studies are necessary to evaluate the long-term behavior of Y-TZP restorations and establish which materials and techniques should be recommended for luting these restorations.

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