Review

An overview of zirconia ceramics: Basic properties and clinical applications

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ABSTRACT

Zirconia (ZrO2) is a ceramic material with adequate mechanical properties for manufacturing of medical devices. Zirconia stabilized with Y2O3 has the best properties for these applications. When a stress occurs on a ZrO2 surface, a crystalline modification opposes the propagation of cracks. Compression resistance of ZrO2 is about 2000 MPa. Orthopedic research led to this material being proposed for the manufacture of hip head prostheses. Prior to this, zirconia biocompatibility had been studied in vivo; no adverse responses were reported following the insertion of ZrO2 samples into bone or muscle. In vitro experimentation showed absence of mutations and good viability of cells cultured on this material. Zirconia cores for fixed partial dentures (FPD) on anterior and posterior teeth and on implants are now available. Clinical evaluation of abutments and periodontal tissue must be performed prior to their use. Zirconia opacity is very useful in adverse clinical situations, for example, for masking of dischromic abutment teeth. Radiopacity can aid evaluation during radiographic controls. Zirconia frameworks are realized by using computer-aided design/manufacturing (CAD/CAM) technology. Cementation of Zr-ceramic restorations can be performed with adhesive luting. Mechanical properties of zirconium oxide FPDs have proved superior to those of other metal-free restorations. Clinical evaluations, which have been ongoing for 3 years, indicate a good success rate for zirconia FPDs. Zirconia implant abutments can also be used to improve the aesthetic outcome of implant-supported rehabilitations. Newly proposed zirconia implants seem to have good biological and mechanical properties; further studies are needed to validate their application.

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1. Introduction

Zirconia is a crystalline dioxide of zirconium. Its mechanical properties are very similar to those of metals and its color is similar to tooth color.1 In 1975, Garvie proposed a model to rationalize the good mechanical properties of zirconia, by virtue of which it has been called “ceramic steel”.2 Zirconia crystals can be organized in three different patterns: monoclinic (M), cubic (C), and tetragonal (T). By mixing ZrO2 with other metallic oxides, such as MgO, CaO, or Y2O3, great molecular stability can be obtained.1 Yttrium-stabilized zirconia, also known as tetragonal zirconia polycrystal (TZP), is presently the most studied combination.3 The aforementioned three phases are present in a common ZrO2 crystal. Every transition between the different crystalline reticulations is due to a force on the zirconia surface, and this produces a volumetric change in the crystal where the stress is applied. When a stress occurs on a zirconia surface, cracking.
energy creates a T–M transition. This crystalline modification is followed by an expansion that seals the crack.\(^4\) \(\text{ZrO}_2\) stabilized with \(\text{Y}_2\text{O}_3\) has better mechanical properties than other combinations; although its sintering is much more difficult, this is the principal kind of zirconia considered for current medical use.

The first proposal of the use of zirconium oxide for medical purposes was made in 1969 and concerned orthopedic application. \(\text{ZrO}_2\) was proposed as a new material for hip head replacement instead of titanium or alumina prostheses.\(^5\) They evaluated the reaction upon placing \(\text{ZrO}_2\) in a monkey femur and reported that no adverse responses arose. Orthopedic research focused on the mechanical behavior of zirconia, on its wear, and on its integration with bone and muscle. Moreover, these first studies were largely carried out in vivo because in vitro technology was not yet sufficiently advanced. Prior to 1990, many other studies were performed, in which zirconia was tested on bone and muscle without any unfavorable results.\(^6\)–\(^11\) Since 1990, in vitro studies have also been performed in order to obtain information about cellular behavior towards zirconia.\(^12\) In vitro evaluation confirmed that \(\text{ZrO}_2\) is not cytotoxic\(^{13\text{-}15}\) (Fig. 1). Uncertain results were reported in relation to zirconia powders that generated an adverse response.\(^6\)–\(^17\) This was probably due to zirconium hydroxide, which is no longer present after sintering so that solid samples can always be regarded as safe. Mutagenicity was evaluated by Silva and by Covacci, and both reported that zirconia is not able to generate mutations of the cellular genome\(^{18\text{-}19}\); in particular, mutant fibroblasts found on \(\text{ZrO}_2\) were fewer than those obtained with the lowest possible oncogenic dose compatible with survival of the cells.\(^19\)

Moreover, zirconium oxide creates less flogistic reaction in tissue than other restorative materials such as titanium.\(^20\) This result was also confirmed by a study about peri-implant soft tissue around zirconia healing caps in comparison with that around titanium ones.\(^21\) Inflammatory infiltrate, microvessel density, and vascular endothelial growth factor expression were found to be higher around the titanium caps than around the \(\text{ZrO}_2\) ones. Also, the level of bacterial products, measured with nitric oxide synthase, was higher on titanium than on zirconium oxide. Zirconia can up- or down-regulate expressions of some genes, so that zirconia can be regarded as a self-regulatory material that can modify turnover of the extracellular matrix.\(^22\)

Zirconia has mechanical properties similar to those of stainless steel. Its resistance to traction can be as high as 900–1200 MPa and its compression resistance is about 2000 MPa.\(^5\) Cylindrical stresses are also tolerated well by this material. Applying an intermittent force of 28 kN to zirconia substrates, Cales found that some 50 billion cycles were necessary to break the samples, but with a force in excess of 90 kN structural failure of the samples occurred after just 15 cycles.\(^23\) Surface treatments can modify the physical properties of zirconia. Exposure to wetness for an extended period of time can have a detrimental effect on its properties.\(^24\) This phenomenon is known as zirconia ageing. Moreover, also surface grinding can reduce toughness.\(^25\) Kosmac confirmed this observation and reported a lower mean strength and reliability of zirconium oxide after grinding.\(^26\)

\section*{2. Clinical aspects}

In the search for the ultimate aesthetic restorative material, many all-ceramic systems have been proposed. Dental research is nowadays directed towards metal-free prosthetic restorations in order to improve aesthetical outcome of FPD restorations. Natural look of soft tissue in contact with fixed partial dentures is influenced by two factors: mucosal thickness and typology of restorative material. Metal-free restorations allow to preserve soft tissue color more similar to the natural one than porcelain fused to metal restorations.\(^27\) Many ceramics, such as spinel, alumina, and ceramic reinforced with lithium disilicate, have been proposed for the construction of metal-free restorations.\(^28\) These materials have precise indications for fixed partial dentures (FPD); Luthy measured average load-bearing capacities of 518 N for alumina restorations, 282 N for lithium disilicate restorations, and 755 N for zirconia restorations.\(^29\) Raigrodski analyzed different all-ceramic systems and concluded that reinforced ceramics can only be used to replace anterior teeth with single crown restorations or maximum with three units FPDs. On the other hand, \(\text{ZrO}_2\) restorations have a wider application field. Other ceramic technologies only allow the construction of structures that are resistant to chewing stresses on anterior teeth. On the contrary, \(\text{Zr}\)-ceramic FPDs can also be used on molars.\(^28\) Tinschert compared lifetime of different metal-free core for FPD and reported that \(\text{Zr}\)-ceramic with alumina oxide had the highest initial and most favorable long-term strength.\(^30\) Connecting surface area of the FPD must be at least 6.25 mm\(^2\).\(^31\) For this reason, ceramic FPDs should only be used when the distance between the interproximal papilla and the marginal ridge is close to 4 mm. In a comparison between 3-, 4- and 5-unit zirconia fixed partial dentures and minimal connecting surface resulted, respectively, 2.7 mm\(^2\), 4.0 mm\(^2\) and 4.9 mm\(^2\).\(^32\) Height of abutment is fundamental to obtain \(\text{ZrO}_2\) frameworks with correct shape and dimension in order to ensure mechanical resistance of restoration. This aspect must

\begin{figure}[h]
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\caption{Scanning electron microscopy (SEM) observation of fibroblasts cultured on zirconia: cells grow on the whole zirconia surface, covering it with a cellular layer. A cellular body covered by cytoplasm is discernible (magnification 7400×).}
\end{figure}
be carefully considered when realizing a metal-free FPD. Zirconia restorations have found their indications for FPDs supported by teeth or implants. Single tooth restorations and fixed partial dentures with a single pontic element are possible on both anterior and posterior elements because of the mechanical reliability of this material.33–35 It is possible to use juxtapositional marginal preparations and various finishing lines to obtain a good aesthetic.36 FPD extension is nowadays a limitation in using Zr-ceramic restorations. Although some manufacturer allows obtaining also full arch restorations, 5 units-FPDs are reported to be as maximal possible.37 As a matter of facts, reliability of greater extensions must be investigated. Some physical properties of zirconia must be considered in order to obtain a good aesthetic outcome. As a matter of fact, zirconia has not only a color similar to teeth but is also opaque38; this can be an advantage for the technician: when a dischromic tooth or a metal post must be covered, a zirconia core allows concealment of this unfavorable aspect (Figs. 2 and 3). On the contrary, if translucency is absolutely needed, it can be attained with other ceramic materials such as alumina or lithium disilicate. Moreover, some manufac-
turers make provision for zirconia colored cores in order to enhance aesthetic outcomes. Preventive evaluation of natural teeth color and transparency is necessary to select an appropriate all-ceramic system. Moreover, when Zr-ceramic restoration is preferred, a preoperative choice between different colored cores is suggested. Also, the radiopacity of zirconia is very useful for monitoring marginal adaptation through radiographic evaluation, especially when intrasulcular preparation is used (Fig. 4).3

In order to produce a ZrO₂ core for a prosthetic restoration, it is necessary to use a computer-aided design/manufacturing (CAD/CAM) system that can deal with zirconia and create a fitting framework. The realization of the Zr-ceramic restorations must be conducted in a precise sequence of steps that involves both the clinician and the laboratory technician. Tooth preparation can be realized with various finishing lines, although chamfer and rounded shoulder are recommended. Preparation must follow the scallop of the free gingival margin; anterior teeth reduction must be at least 1.5 mm incisal and of 1.0 mm axial on margin with a 4°6° taper; axial reduction in aesthetical areas can be extended up to 1.5 mm. Posterior teeth should be prepared with 1.5 mm of occlusal reduction and with 1.0 mm of axial reduction on marginal region with a 4°6° taper.39,40 After conventional impression procedures are performed, a master die is created and a CAD/CAM procedure is followed. Scanning procedure can be influenced by many factors that clinician and technician must control to optimize marginal fit of restoration. External line angle of preparation must be linear to allow an adequate scanning. Moreover, accurate impression and master die preparation must be performed to prevent mismatch between framework and abutments.41 After die scanning, it is possible to realize a zirconia core by means of a CAD/CAM system in two different ways42,43: milling a fully sintered piece of zirconia, or milling a partially sintered zirconia block and then completing the sintering thereafter. As a matter of fact, fully sintered zirconia is very hard, which makes milling very difficult; moreover, milling operations can be detrimental to the mechanical properties. On the other hand, if zirconia is cut before fully sintering, a 20% shrinkage must be allowed for in order to obtain a fitting core. Although this second system can create superior
structures, organization and management of the production is more demanding. Zirconia sintered after milling has better mechanical properties than densely sintered zirconia; moreover ceramic veneering can improve ZrO₂ fracture strength. Comparing different core designs a higher fracture strength was found when Zr core thickness is optimized in order to obtain a uniform thickness of veneer ceramic. After clinical control of the core adaptation, technician can realize ceramic veneering.

Zirconium oxide–ceramic relationship is not yet well known. Core–veneer interface is one of the weakest aspect of these restorations so that ceramic chipping or cracking are possible. Different factors may influence veneer cracking as differences in thermal expansion coefficients between core and ceramic, firing shrinkage of ceramic, flaws on veneering and poor wetting by veneering on core. Special ceramics are nowadays developed for zirconia in order to minimize this unfavorable aspect, but more evaluation of zirconia core–veneer bond must be performed. After veneering control and finishing, luting of restoration can be performed (Fig. 5).

Resin-bonded luting has proved to be the best choice for Zr-ceramic restorations, although the use of conventional cementation may also be permissible. Bindl et al. reported that conventional luting did not reduce fracture resistance of Zirconia-ceramic restoration. Derand and Derand reported a shear bond strength of 8.9 MPa for a zirconium restoration with resin-bonded luting. Palacios et al. measured shear bond strengths of resin cementation of between 5.1 and 6.0 MPa depending on the luting agent. Blatz et al. reported a shear bond strength of 16.85 MPa for self-etching bonding adhesive cementation after 180 days of thermal cycling; Atsu et al. compared shear bond strength of zirconia-ceramic restoration without surfacial treatment (15.7 MPa), with silanization (16.5 MPa) and with trebochemical treatment (22.9 MPa). Kern and Wegner underlined that airborne or silane utilization did not improve resin bond adhesion on zirconia. Nowadays there is no accordance in results between different studies about luting procedures for Zr-ceramic restoration. The need of internal surface treatment requires further experimental evaluation. Airborne and silanization result not influencing adhesion; trebochemical treatment seems to improve bonding.

Surface treatment seems to be unnecessary to obtain good adhesion. At the present time Zr-ceramic restorations should be luted with resin cement without surface treatment or, at least, with trebochemical treatment. In our opinion, from a clinical standpoint, resin cementation appears one of the most favorable choices in order to obtain adequate values of adhesion and good mechanical features of ZrO₂ restorations.

The mechanical resistance of zirconia FPDs has been studied on single tooth restorations and on three or four-unit FPDs. The numerical results are not consistent if the different studies are compared; Tischert et al. reported a fracture load for ZrO₂ of over 2000 N, whereas Sundh et al. measured fracture loads in the range 2700–4100 N, whereas Luthy et al. asserted that a zirconia core could fracture under a load of 706 N. However, these results are not directly comparable because the methods of measurement were not standardized between the studies. On the other hand, in each of these tests it was demonstrated that zirconia restorations yield superior results in terms of fracture resistance as compared with alumina or lithium disilicate ceramic restorations.

Ageing of Zirconia can have detrimental effects on its mechanical properties. Mechanical stresses and wetness exposure are critical to accelerate this process. Nowadays effects of ageing on zirconium oxide used for oral rehabilitation are not yet well known. By an in vitro simulation resulted that, although ageing reduce mechanical features of Zirconia, resistance values decrease into clinical acceptable values. Further evaluations are needed because zirconia behavior in long time period is not yet investigated. Moreover relationship between ageing of ZrO₂ frameworks and long term loading must be evaluated.

By using CAD/CAM technology, it is now possible to obtain zirconia implant abutments. Replacing missing teeth with an implant-supported FPD requires functional and aesthetic evaluation by the clinician. In order to achieve a good outcome for an implant-supported FPD, many aspects need to be considered. A natural-looking emergence must be obtained in order to harmonize restoration and natural teeth. Intruscular abutment design is critical to reduce the risk of metallic blue shimmer through thin soft tissue. The use of ceramic abutments reduces this risk, allowing for optimal adaptation between the margins of the restoration and the soft tissue (Figs. 6 and 7).

Precision at the implant interface between the abutment and the fixture was assessed by comparing the rotational freedom of titanium, alumina, and zirconia abutments with hexagonal external connections. Titanium and zirconia each showed a significantly lower mean rotational freedom compared to the alumina abutment. The rotational freedom between the abutment and the fixture amounted to less than 3° for all of the abutments studied. In another study, it was reported that a zirconia abutment with a machined titanium base had a rotational freedom of less than 3°. Moreover, abutments milled by means of CAD/CAM systems can also be modified by the clinician to obtain a better marginal adaptation. In a study about 54 zirconia implant abutments, after 4 years neither of them showed structural failure with good peri-implant tissue health. Though these studies indicate that ZrO₂ abutment could be suitable for clinical use for single tooth implant replacement, some aspects must be evalu-
ated. In particular, a possible wear behavior under loading at the implant/abutment interface between titanium external connection and zirconia abutment must be investigated. As a matter of fact, wear can reduce both mechanical properties of zirconia and the fit between implant and abutment. Moreover, the resistance of screwing abutment must be evaluated; minimal thickness of abutment walls must be established in order to perform adequate screwing torque of abutment without compromising zirconia abutment resistance.

Butz et al. evaluated the survival rate, fracture strength, and failure mode of this kind of abutment and concluded that after chewing simulation and fracture loading, ZrO2 abutments were comparable to titanium ones (281 N as opposed to 305 N). Also, the fracture rate of zirconia abutments was similar to that of their titanium counterparts.

Bacterial adhesion, which is an important aspect in order to maintain zirconia restorations without marginal infiltrations or periodontal alterations, proved to be satisfactorily slight; Scarano et al. reported a degree of coverage by bacteria of 12.1% on zirconia as compared to 19.3% on titanium. Rimondini et al. confirmed these results with an in vivo study, in which Y-TZP accumulated fewer bacteria than Ti in terms of the total number of bacteria and presence of potential putative pathogens such as rods. Surfacial roughness in this context appears very important; Kou et al. compared different polishing systems for zirconia and concluded that polishing creates surfaces similar to the just sintered ones and smoother than only grinding surfaces. These studies indicate that zirconium oxide can be suitable for implant abutment but more clinical and mechanical trials are necessary for a complete understanding of behavior of zirconia abutment throughout a long time period. Edelhoff has proposed inlays and onlays with a zirconium oxide core. In order to realize these restorations, an occlusal reduction of almost 2 mm is necessary, and the axial reduction must be of 1.5 mm with a cavosurface angle of 100–120°.

Zirconia implants are a recent proposal. In a clinical case, Khoal reported an all-ceramic custom-made zirconia implant-crown system for the replacement of a single tooth. In an experimental study in rabbits, mean bone implant surface was reported about 68.4%. Sennerby compared the osseointegration and removal torque of zirconia implants, titanium oxide implants, and zirconia with a modified surface when these were inserted in the tibia and femur of rabbits. He concluded that although osseointegration appeared similar between the different samples, the removal torque of the pure zirconia implant was lower than those of the other two implants, suggesting that surface modification can improve zirconia implant stability. Titanium implants with a coronal base in zirconia are also available, the aim of which is to combine the safety of titanium with the aesthetic features of zirconia. Moreover, an in vitro experimental study, pointed out that zirconia implants are able to sustain chewing stresses. Cyclical mechanical resistance of zirconia implants with ceramic restorations in comparison with that of traditional implant-prosthodontic restorations was studied. The mean fracture load after cyclical stress in titanium-porcelain fused to metal restorations amounted to 668.6 N, whereas for zirconia implants with all-ceramic restorations fracture occurred at a mean load of 555.5 N. It was concluded that ZrO2 implants are able to bear fatigue and stresses sufficiently well for anterior teeth implant replacement.

Suarez studied the outcome 3 years after the placement of ZrO2-ceramic restorations on 18 teeth. Only one tooth had failed after the experimental period because of radicular fracture. According to this study, it is possible to consider zirconium oxide restorations as reliable for clinical use. Raigrodski et al. studied the durability of three-unit zirconia FPDs and asserted that these also showed a good outcome after 3 years. This result is in agreement with a study by Sailer et al., in which a similar outcome was found for restorations of this kind. A systematic review of the literature evaluated all-ceramic restorations survival rate in comparison with porcelain fused to metal and, inside all ceramic group, with zirconia ceramic restorations.

**Fig. 6** – Labial view of customized zirconia implant abutment on right maxillary central incisor (#1.1): note the submarginal emergence profile of the abutment and the support of the peri-implant soft tissue.

**Fig. 7** – Scanning electron microscopy (SEM) observation of the implant interface between a zirconia CAD-CAM abutment and a fixture with a hexagonal external connection: the zirconia abutment is perfectly fitted and screwed onto the implant hexagonal connection (magnification 30.2×).
survival rate of all-ceramic restorations resulted 93.3%, whereas metal-ceramic restorations have a 5-years survival rate of 95.6%. In particular, all ceramic restorations on posterior teeth resulted to have the worst 5-year survival percentage (84.4%). These results did not considered zirconia restorations. On the other hand, when comparing Zr-ceramic restorations with other all-ceramic systems, zirconia frameworks resulted as the most reliable. The weakest point of these restorations resulted veneering chipping or cracking whereas other all-ceramic restorations showed a percentage of framework fracture. These results are in accordance with clinical indication for all ceramic restorations that indicates that all ceramic systems can be used preferably on anterior teeth; only zirconia showed adequate mechanical resistance for both anterior both posterior restorations. More clinical long term evaluation must be performed to understand behavior and reliability of zirconia compared with porcelain fused to metal restorations that are, nowadays, the most reliable system for FPD restorations.

3. Conclusion

Although clinical long-term evaluations are a critical requirement to conclude that zirconia has good reliability for dental use, biological, mechanical, and clinical studies published to date seem to indicate that ZrO₂ restorations are both well tolerated and sufficiently resistant. Ceramic bonding, luting procedures, ageing and wear of zirconia abutment should be evaluated in order to guide adequate use of zirconia as prosthetic restorative material. Patient selection, coupled with adequate clinical and technical protocols, are imperative in order to obtain good performance of these restorations.

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