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Zirconia Ceramic: A Versatile Restorative Material

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Abstract

Metal ceramic restorations were considered the gold standard as reliable materials. Increasing demand for esthetics supported the commercialization of new metal free restorations. A growing demand is rising for zirconia prostheses. Peer-reviewed articles published till September 2013 was identified through a Medline. Emphasizing was made on zirconia properties and applications. Zirconia materials are able to withstand posterior physiologic loads. Although zirconia cores are considered as reliable materials, these restorations are not problem free.

Keywords: Zirconia ceramic; Ceramic restorations; Zirconia cores

Introduction

In the last two decades, full ceramic restorations have become increasingly popular thanks to their aesthetics when compared to metal-ceramic restorations. Ceramic materials have a tooth-like color and can be shaded to match the natural adjacent tooth resulting in a higher overall aesthetic and greater patient satisfaction. Zirconia has been recently introduced in prosthetic dentistry for the fabrication of crowns and fixed partial dentures, in combination with CAD/CAM techniques. This paper discusses the properties of Zirconia material. The two main processing techniques, soft and hard machining, will be assessed in the light of their possible clinical implications and consequences on the long-term performance of zirconia.

Background

All-ceramic dental materials can be very different in their chemical composition as well as in their structure and therefore demonstrate very different material properties. In dentistry there are three different groups of ceramics: polycrystalline ceramics, glass infiltrated ceramics and glass ceramics [1]. Veneer ceramics are feldspathic porcelains which consist almost entirely of an amorphous glass phase and therefore deliver ideal optical characteristics for the veneering.

Glass ceramics and glass infiltrated ceramics are multi-phase materials and contain crystalline constituents (e.g. leucite crystallites in the glass ceramic Empress® II, Al_2O_3-crystals in infiltrated ceramics etc.) in addition to an amorphous glass phase.

Aluminia and zirconia are the only two polycrystalline ceramics suitable for use in dentistry as framework materials able to withstand large stresses. These materials are shown to provide both necessary esthetics (tooth color) and material properties required of a modern tooth restoration [2].

Pure polycrystalline oxide ceramics are available for clinical use (e.g. Procera®). For the first time they displayed a type of material that possesses sufficient stability for posterior applications. Pressed ceramics, such as Empress, have been used successfully only for anterior crown applications for more than 10 years [3]. They were not indicated for bridges or fixed partial dentures for posterior applications. In view of the success of porcelain fused to metal for over 30 years (a minimum survival rate of 85 % after 10 years in situ is required – even for posterior bridges), any new all-ceramic system must be comparable to this standard. Moreover, favorable conditions for a high survival rate of the all ceramic material that has been used, were also due to the adhesive bonding of Crowns and Bridges [4,5]. The reason is a less critical stress situation and therefore a stabilization of relatively fracture susceptible glass ceramics by adhesive bonding. The conventional cementation, although less technically sensitive, was however, contra-indicated [6,7].

As a result of the requirement to provide patients with high quality, esthetic and biocompatible prosthetic dental restorations, the search for ways to fabricate all-ceramic multi-unit bridges, offering long-term stability also especially in posterior applications, has witnessed the limitations of glass ceramics and infiltrated ceramics.

Because of their material characteristics, frameworks based on polycrystalline ceramics are able to surmount these limitations. Bridges for the posterior region are also considered as an indication. It is zirconium oxide (zirconia), with its excellent strength and biocompatibility known from implant prosthetics that makes it the framework material of choice.

The zirconia framework also has to be the foundation of optimal esthetics (translucency & color) in combination with perfectly matching overlay porcelain.

Due to the enormous strength and the natural esthetics of the framework, a tooth structure saving preparation as well as traditional cementation techniques, as used in luting porcelain fused to metal, are possible [8].

Nowadays, several companies are offering zirconia materials in dentistry. These materials are chemically similar, consisting of 3% yttrium oxide treated tetragonal zirconia polycrystals. In many cases they are also treated with a very small concentration of alumina (<0.25 %) to prevent leaching of the yttrium oxide. This combination ensures the safety and longevity of zirconia restorations.

In principle, there is pre-sintered zirconia and HIP (hot isostatic pressing) zirconia available on the market.

The pre-sintered zirconia is milled, when the material still has a soft, chalk-like consistency. After milling in the pre-sintered state, the enlarged geometry is sintered pressureless in a furnace at temperatures

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between 1,350°C and 1,500°C. The porous pre-sintered zirconia shape shrinks by approximately 20% to 25% linear, thus achieving its strength and optical properties.

HIP material is milled in the fully sintered state. The chemical composition of HIP zirconia is exactly the same as that which is utilized for the green machining approach. HIP stands for "Hot Isostatic Pressing." By means of comparison, in a closed system, high temperatures and pressures are applied to densify the material a bit more than the non-HIP zirconia, gaining approximately 20% more in strength [9,10].

The Cercon and Lava systems use partially sintered Y-TZP–based blanks for milling the infrastructures, whereas the DC-Zirkon infrastructures are milled from fully sintered Y-TZP–based blanks by the DCS-Precident system. With a partially sintered milled framework, the size has been increased to compensate for prospective shrinkage (20%-25%) that occurs during final sintering [11,12]. The milling process is faster and the wear and tear of hardware is less than the milling from a fully sintered blank [13]. The proponents of partially sintered frameworks claim that microcracks may be introduced to the framework during the milling procedure of a fully sintered blank [14] whereas the proponents of milling of a fully sintered blank claim that because no shrinkage is involved in the process the marginal fit is superior [13].

Zirconia is a material regarded as having the highest strength and fracture toughness in dentistry. The available zirconia powders can have different grain sizes, different distributions of the various grain sizes, and different additives (e.g., binder for the pressing step). The additives yttrium oxide and alumina can be distributed within the material in a variety of ways such as a homogeneous distribution throughout the whole material, higher concentration at grain borders, etc. The grain size has an effect on strength and transformation toughening, a special and key mechanical characteristic of zirconia. Variations in grain size distribution affect the resulting porosity and hence the translucency of the material. The distribution of additives can affect the hydrothermal stability of the sintered material.

Biocompatibility

A small percentage of the population is hypersensitive to dental alloys containing both noble and base metals, such as palladium and nickel. Metal-free ceramic systems eliminate this problem [15]. All-ceramic tooth restorations are considered inert with respect to oral stability and biocompatibility. The biocompatibility of YTZP was evaluated in both *in vitro* and *in vivo* studies with no reported local or systemic adverse effects from the material [16,17]. The accumulation of plaque is comparable to that on the natural tooth. The findings demonstrated that fewer bacteria accumulated around Y-TZP than titanium in terms of number and presence of pathogens such as rods [18,19]. Due to the low thermal conductivity of the ceramic, (unlike metal-supported units), sensitivity to temperature variation is no longer expected.

Long-Term Stability

A dental material needs to adjust to the different influences and conditions of the oral environment. The main concern centers on adequate long-term strength under functional stress in the specified range of indications. From the clinical point of view, it is not the initial strength of the ceramic material itself that is of prime importance, but the time that the permanent restoration will last.

It should have high stability in order to spontaneously withstand extreme stresses and high fracture toughness. Various examinations prove higher stability of infiltrated ceramics than of glass ceramics [20-22] with the highest stability measured in polycrystalline ceramics [20,21,23-27].

Next to the initial stability, especially the long-term stability is the deciding factor in the clinical success of the different systems. Therefore, the question of long-term stability which is highly dependent on subcritical crack growth and fatigue is an exceptionally important aspect in the assessment of new all-ceramic systems. An after-treatment of all-ceramic can induce micro defects, which can grow by subcritical crack growth until a critical crack length leads to fracture. The subcritical crack growth velocity is an essential parameter of ceramic material which can greatly differ from material to material. It indicates the speed at which an existing defect in the oral environment can grow subject to static and/or dynamic stress, until it results in a complete failure [28]. The speed of crack growth also depends on the surrounding medium as well as the previously mentioned fracture toughness. H_2O in the saliva leads to so-called stress corrosion in systems containing glass (glass ceramic and infiltrated ceramic). The water (saliva) reacts with the glass causing corrosion of the latter, leading to increased crack propagation velocities. On the other hand, systems having a polycrystalline micro-structure, such as ZrO_2 or Al_2O_3 are to a greater extent glass-free and display excellent long-term stability [27].

Zirconia used in demanding environments is usually a tetragonal polycrystalline zirconia partially stabilized with yttria (Y-TZP = yttria tetragonal zirconia polycrystals) (addition of about 3 mol%). This material is referred to as a transformation toughened material and it has the special property of a certain fracture inhibiting function. Tensile stresses acting at the 'crack tip' induce a transformation of the metastable tetragonal zirconia phase into the thermodynamically more favorable form. This transformation is associated with a local increase in volume, resulting in localized compressive stresses being generated at the 'crack tip', which counteract the external stresses acting on the crack tip. The result is a high initial strength and fracture toughness and, in combination with a low susceptibility to stress fatigue, an excellent life-time expectancy for zirconia frameworks [29].

There is more noticeable loss of strength with glass containing systems due to the effect of oral moisture and subcritical crack growth. Zirconia demonstrates no measurable solubility or water absorption and shows a high initial stability and excellent long term stability. Therefore, the strength of this material is maintained, even after a long period in the mouth [27,30,31].

To guarantee successful long-term restorations, and to allow for the material to fatigue with a prospective safety margin, an initial strength of approximately 1000 N is necessary for posterior applications [32].

Moreover, considering the maximal forces of 400 N in the oral anterior area and 600 N in the oral posterior area, only zirconia can guarantee the initial strength that is needed for inserting multi-unit bridges [33]. Zirconia withstands many times the load level occurring in the mouth (loads measured for anterior teeth up to 400 N, posterior teeth up to 600 N, for bruxism even up to 800 N [34-36].

Long-term stabilities can also be determined by artificial ageing of the specimen. Thereby, the cyclic masticatory forces and thermal fluctuation in the oral environment are simulated after which the strength of the specimen will be determined. Studies did not notice any significant decrease in strength zirconia, after the specimen was cyclically loaded [26,37].

Y-TZP–based cores present with a metal-like radiopacity that enhances radiographic evaluation of the restoration [38]. As a result of their mechanical and physical properties, Y-TZP–based FPD frameworks require a relatively small connector area compared to other allceramic core materials, such as glass-infiltrated alumina, glass-infiltrated alumina with 35% zirconia, and lithium disilicate, ranging between 7 and 16 mm^2 [11-13].

Accuracy of Fit

Not the least consideration, a good accuracy of fit is also a determining factor for clinical success. An accuracy at the crown margin of 50 µm - 100 µm is considered ideal [39,40].

These requirements can now be achieved using precise scanning and milling technologies coupled with accurate knowledge of the zirconia ceramics and their outstanding mechanical and optical properties [41-43].

Conventional Working Method and Cementation

Ideally, the practitioner needs a system that does not require him/her to change preparation and/or impressioning methods. The optimal system would use supragingival preparations where less tooth structure is removed, as compared with porcelain fused to metal restorations.

Traditional luting, e.g. glass ionomer cements, would simplify the cementation process – and have the advantage of many years of success [44].

In the case of ceramics containing glass, the type of cementation, adhesive bonding or conventional, is usually a decisive factor. It has a considerable effect on the stresses acting on the entire tooth preparation/restoration system. Adhesive bonding is required e.g. in the case of a flexural strength of around 350 MPa and a fracture toughness <2 MPa•m1/2 (typical for glass ceramics) [32].

In the case of polycrystalline ceramic frameworks with considerably higher strength values, conventional cementation using glass ionomer cements may be recommended. Zinc phosphate cement is not indicated for esthetic reasons.

Adhesive cementation may be used but is not mandatory, and traditional luting agents, including glass-ionomer cements, resin-modifed glass ionomer cements, and composite resin luting agents, may be used [11-13].

However, in the case of adhesive cements, it needs to be considered that zirconia, unlike glass ceramics, cannot be etched and therefore a silicatization/silanization (e.g. Rocatec™) for the bonding is necessary. Exemptions are self-adhesive cements which allow a direct chemical bonding with zirconia [45].

When sandblasting a material it is bombarded by particles of different grain sizes. The aim of sandblasting is to increase the surface area and obtain higher surface roughness and/or to purify the material [46].

In general, the intaglio surface of the restoration is sandblasted in order to get a higher surface. The cement can optimally wet the larger interface resulting in better mechanical retention of the restoration [47]. Often, the outer surface of the restoration framework has been sandblasted for the same reason to optimize the interface to the veneering. However, in the case of CAD/CAM milled zirconia restorations, the sandblasting of the outer surface is not necessary. In addition, transformation processes may occur on the outer surface resulting in a change in the coefficient of thermal expansion (CTE) of the material [48].

For chemical bonding with adhesive cement, glass ceramic materials are etched by hydrofluoric acid (HF) in order to increase the surface and are subsequently silanized to get a chemical bonding between the inorganic ceramic material and the organic resin material of the cement. In the case of zirconia, this is not possible due to the special chemistry of the material [49]. Furthermore, zirconia has no specific groups to bond to the silanization agent. Therefore, the zirconia has to be treated with Rocatec Soft bonding material. Through this treatment, by tribochemical reaction, the surface of the zirconia is coated with small particles of silicium oxide. These can bind to the silanization agent and establish a chemical bonding to the adhesive resin cement [37,50,51].

Surface Finishing

The surface finishing of ceramic materials has a decisive effect on the material's flexural strength. The grinding and milling of sintered ceramics usually leads to a reduction in strength (micro defects on the surface) of the total restoration. The finishing, by grinding or milling, of sintered zirconia frameworks (either by means of the fabrication process, or finishing in the dental laboratory) may lead to a loss of strength compared to finishing in the green, or pre-sintered state. The finishing of sintered frameworks using grinding or milling tools is contra-indicated on the gingival side of the connector area because here enhanced tensile stress is formed.

After milling and sintering, the internal surface of the crown shows an efficient micro-retention for bonding with the cement. If, however, after-treatment is still necessary, fine-grained diamonds (<40 µm;) and water cooling must be used [27].

Optical Properties/Esthetics

Aesthetics is of course a very subjective attribute, but it can be evaluated by analyzing characteristics such as color (shade match) and translucency of the material as these seem to have the greatest influence on the patient's perception of the dental restoration [52].

Afterwards, restorations made from ceramic frameworks have to be esthetically veneered. Thereby the coefficients of thermal expansion (CTE) of both ceramics have to be checked against each other, especially for zirconia which shows a relatively low CTE (approx. 10 ppm). Special veneer ceramics with the same or lower CTE have been developed during the last few years [53].

The translucency of the material depends on the material properties of the ceramic [54]. No light-absorbent opaquer or opaque dentine layers are necessary. It also relates on the recommended thickness of the layer, i.e. the wall thickness. zirconia requires less wall thickness due to its stability (Lava™ Frame zirconia: 0.5 mm; Empress® II: 0.8 mm) [55].

CAD/CAM manufactured frames of the high-performance ceramic zirconia turned out to be a perfect basis for dental restorations. Ideally, the frame has the colour of the dentin. Thus, highly aesthetic results are even possible in a restricted area which offers space only for thin veneering layer thicknesses [56].

Historically, for colouring ceramics the preferred method was to add colouring pigments before firing. This is the typical way of colouring e.g. glass ceramics and veneering ceramics respectively.

However, for polycrystalline ceramics like zirconia or alumina, adding colour to the base material is more difficult than to glass or veneering ceramics, since the firing temperature is high. Instead, colouring ions are used in order to attain a dentin like colour. The pre-sintered restoration is immerged in shading liquid containing different colouring ions. In the presintered state the material is still porous and can be soaked up by the colouring liquid. The ions diffuse into the zirconia material and are incorporated in the structure during the final sintering step [51,57].

The ability to control the shade of the core may also eliminate the need to veneer the lingual and gingival aspects of the connectors in those situations where the interocclusal-distance is limited and the required connector dimensions are minimally achieved. In addition, the palatal aspect of anterior crowns and FPDs may be fabricated of the core material exclusively in situations of extensive vertical overlap and lack of space for lingual veneering porcelain [38].

Failures

Bulk fracture appears to be quite uncommon in all studies to date. The fractures that have occurred mostly involve connectors of multi-unit prostheses (≥ 4) or second molar abutments [58]. Results for single-unit molar prostheses may turn out to be at least as good as for alumina-based core systems [9].

Problems with the porcelain veneer seem to trouble all studies. In three published reports of four separate systems, 8, 15, 25 and 50% of prostheses developed crazing or cracking with minor loss of material after only 1-2 years of observation [59-61]. This may signal that the difficulties are material-specific, as was the conclusion in one published study of two systems exhibiting, respectively, 8 and 50% incidence of porcelain cracking [60]. It may also indicate that non-materials factors such as thickness ratios or framework design play a role in porcelain cracking [9]. For comparison, porcelain problems on metal–ceramic prosthesis over a 10 years observation period was reported to be on the order of 4% for a gold–palladium alloy, no higher than 6% for most alternative alloys, and only as high as 15% for one nickel-based alloy without beryllium [62]. Consistent findings have been reported for another goldbased alloy, with 98% completely intact porcelain at 5 years [63]. Thus, porcelain–zirconia compatibility appears problematic in light of past experience with metal–ceramic systems [9].

Discussion

Conventional lost wax technique (LW) is still considered as reliable procedure for the construction of fixed partial dentures (FPDs). This provides an acceptable fit and consistent longevity [64]. Newer technologies have been introduced to the market. The CAD/CAM technique contains fewer production steps compared to the LW technique [65].

In the meantime, all clinical studies available on zirconium oxide restorations document a high stability of the structure with high survival rates over an observational period of up to 5 years. At the same time, the clinical studies showed an increased rate of technical complications, e.g. fractures of the veneering ceramics which mainly occurred in the molar region.

The long-term success of veneered zirconia restorations seems to be determined by the weak performance of the veneering ceramics and its limited bond to the zirconia substrate. Delaminations with exposure of the zirconia core ceramic [66] and minor chip-off fractures [62] of the veneering ceramic were described as the most frequent reason for failures of zirconia FPDs. Chip-off fracture rates at 15% after 24 months [19] 25% after 31 months [62] and 8% and 13% after 36 and 38 months, respectively [66], were observed.

The cause of fracture of veneering ceramics on zirconia all-ceramic cores was reported to be multifactorial in clinical application. Restoration geometry such as lack of proper veneering ceramic support, inadequate framework design and thickness of the ceramic layers seem to play a decisive role [66]. Moreover direction, magnitude and frequency of the applied load as well as size and location of occlusal contact areas can contribute to failures of the veneering ceramic [19,62].

Conclusion

New high-strength core/framework materials have been developed for all-ceramic FPDs. However, most of these systems are limited with respect to replacement of the anterior and premolar teeth, require large connector dimensions, and may require the use of more technique-sensitive clinical procedures such as adhesive cementation. The most contemporary systems use YTZP as the core material and may be an alternative treatment modality for replacing a missing tooth both in the anterior and in the posterior segments. In addition, such systems may prove to be simple to handle and less technique- sensitive from a clinical standpoint, while providing patients with esthetic and functional restorations. Still, long-term results of clinical studies are critical to the assessment of long-term success and for the establishment of more specific guidelines for their use.

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