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Zirconia-Modern alloy/ceramic in Dentistry: A review

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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 crack. Orthopaedic 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 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. 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.

Keywords: biocompatibility, fixed partial denture, implants, zirconia

Introduction

Zirconia holds a unique place amongst oxide ceramics due to its excellent mechanical properties [1]. The recent introduction of zirconia-based ceramics as restorative dental materials has generated considerable interest in the dental community. The mechanical properties of zirconia are the highest ever reported for any dental ceramic. This may allow the realization of posterior fixed partial dentures and permit a substantial reduction in core thickness. These capabilities are highly attractive in prosthetic dentistry, where strength and esthetics are paramount. However, due to the metastability of tetragonal zirconia, stress-generating surface treatments such as grinding or sandblasting are liable to trigger the $t \rightarrow m$ transformation with the associated volume increase leading to the formation of surface compressive stresses, thereby increasing the flexural strength but also altering the phase integrity of the material and increasing the susceptibility to aging [2].

Different types of zirconia ceramics available

1. Zirconia toughened ceramic

Pure zirconia (ZrO2) was of very limited interest as a structural or engineering ceramic, and its use was restricted to refractory applications. Claussen has categorized three main groups of Zirconia Toughened Ceramic. Zirconia Toughened Ceramic systems has led to the emergence of three favored systems: Partially Stabilized Zirconia, Tetragonal Zirconia Polycrystal, and dispersed zirconia ceramics [3].

2. Dispersed zirconia ceramic

Zirconia/Oxide Systems

The most commonly exploited DZC system has been that of ZrO2-toughened Al2O3 (ZTA). This system has been utilized primarily for grinding media and metal-cutting-tool applications using material in which the ZrO2 addition takes the unsterilized form.

Efforts to improve the mechanical properties of ZTA systems have been concerned with the assessment of the effectiveness of various solute additions to the ZrO2 and with estimates of the residual stress in the fabricated composites (fig-1) [3].

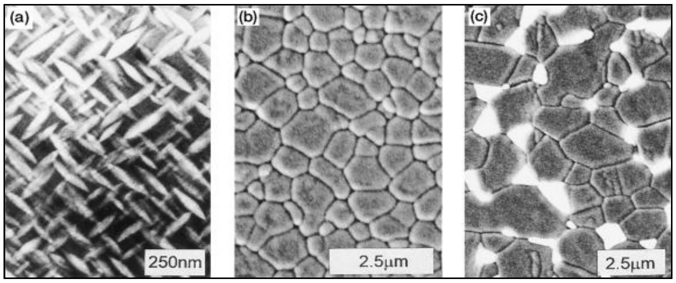

Fig 1

Typical microstructures of the three common forms of TTZ alloy: (a) TEM micrograph of *t* precipitates in Mg-PSZ; and SEM micrographs of (b) Y-TZP and (c) ZTA. In (c), the ZrO2 grains are in bright contrast

Zirconia/Non-oxide Systems

By comparison with other work on ZrO2-toughened systems, relatively little data has been reported on ZrO2 toughening of non-oxide systems. This lack of data may be due to the difficulty in preparing non-oxide ZTC systems such that the metastability of the *t* phase is retained after the high-temperature fabrication process.

3. Partially stabilized zirconia

Partially stabilized zirconia-generally consisting of a *c*-ZrO2 matrix with a dispersion of *t* precipitates [3]. The mechanical strength of PSZ was improved by a homogeneous and fine distribution of the monoclinic phase within the cubic matrix. Study showed how to make the best of T-M phase transformation in PSZ improving mechanical strength and toughness of zirconia ceramics. PSZ can also be obtained in the ZrO2-Y2O3 system (Fig. 2).

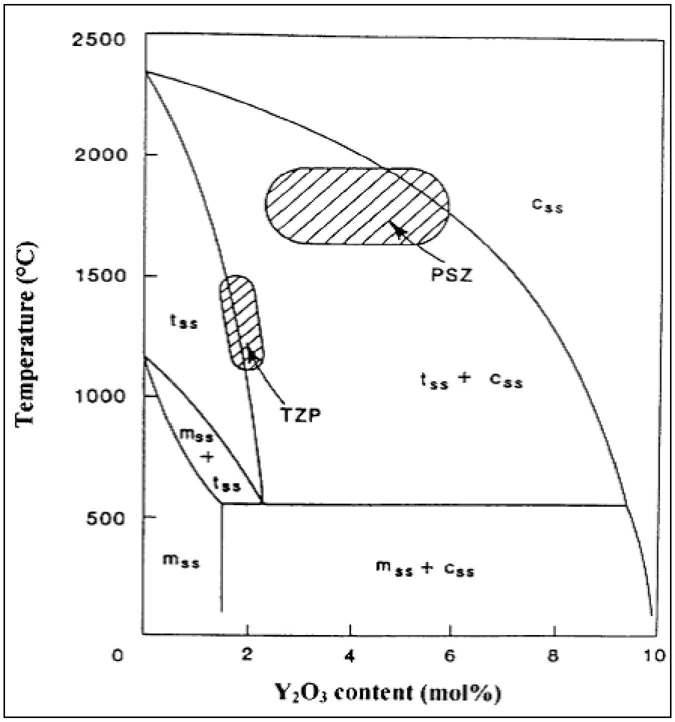

Fig 2: High zirconia part of zirconia-yttria phase diagram. Commercial PSZ and ZTP composition and processing temperatures are indicated by shaded regions.

4. Tetragonal zirconia polycrystalline

Tetragonal zirconia polycrystals-a ZrO2-based ceramic where the matrix grains are stabilized, generally, to a single-phase *t* form at room temperature (two most common forms of TZP are often prefixed with Ce- or CeO2- to denote ceria-stabilized or with Y-or Y2O3- to denote yttria-stabilized, and a number in front of the acronym generally denotes the mole percent of dopant [3]. Mechanical properties of TZP ceramics (Figs. 3 and 4) depend on the size of grains.

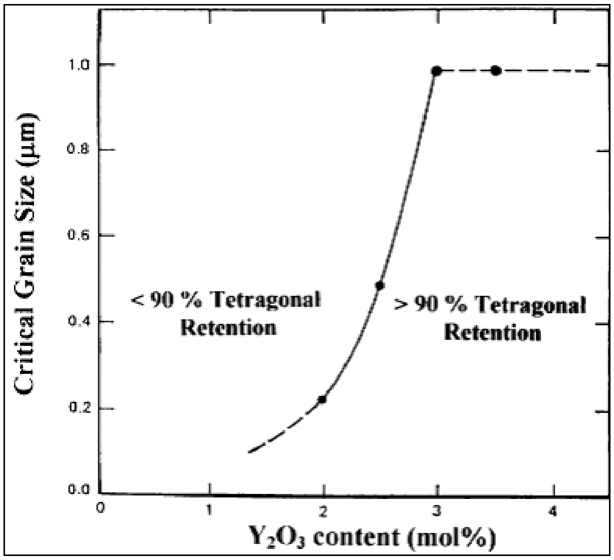

Fig 3: Retention of tetragonal phase. Critical grain size against Yttria content in tetragonal zirconia

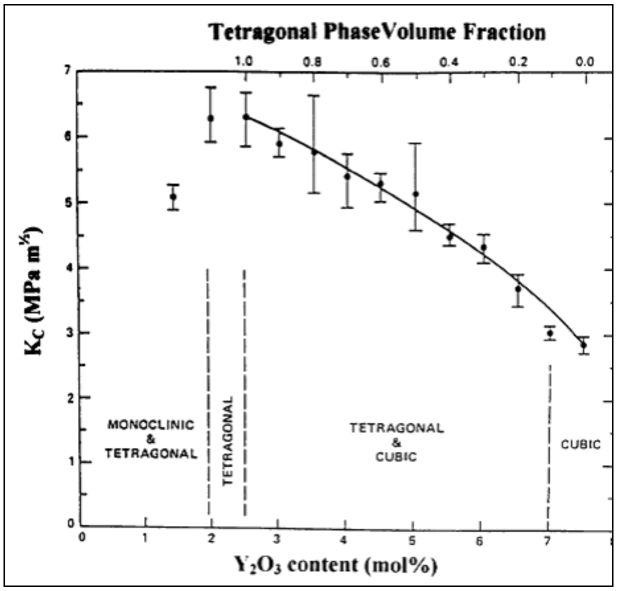

Fig 4: Fracture toughness vs. yttria content

5. (TTC) Transformation-toughened ceramics

Transformation-toughened ceramics-ceramics whose mechanical properties have been improved through the addition of a ZrO2 constituent, generally culminating in a single phase or particle/ precipitates in a host matrix that may or may not be ZrO2 [3].

An important aspect of the mechanical behaviour of transformation toughened Zr02-containing ceramics is their pronounced R-curve behaviour i.e. the phenomenon wherein crack resistance increases with increasing crack propagation. R-curve behaviour due to crack tip transformation showed in (fig.5&6).

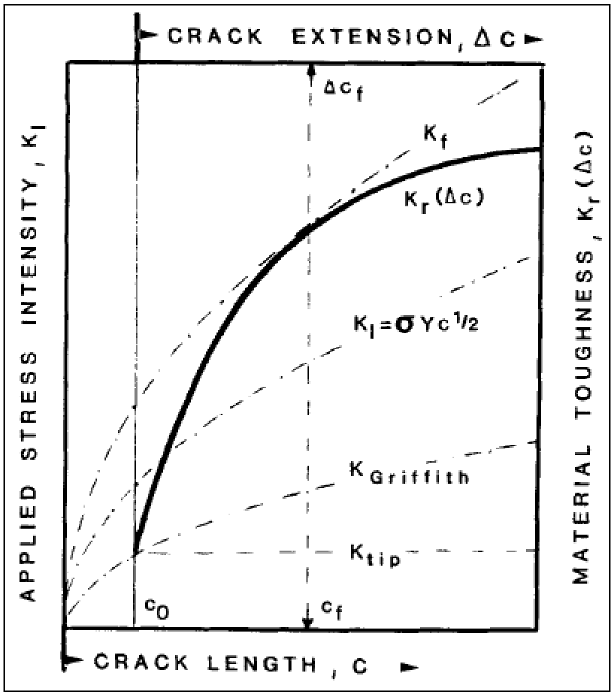

Fig 5: Resistance-curve (R-curve) controlled fracture in ZrO,-toughened ceramics.

The crack driving force K_1 is plotted at the left, while the material toughness, K_r, is shown at the right (heavy curve). When the tip stress intensity factor reaches the Griffith value ($K_{GrlftlIhsr}$) stable crack growth ensues. With increasing applied stress *u*, and crack extension Ac, the crack follows the heavy curve until the instability point K_f, when Ac has grown to be Ac, and the applied stress intensity factor is tangent to the R curve.

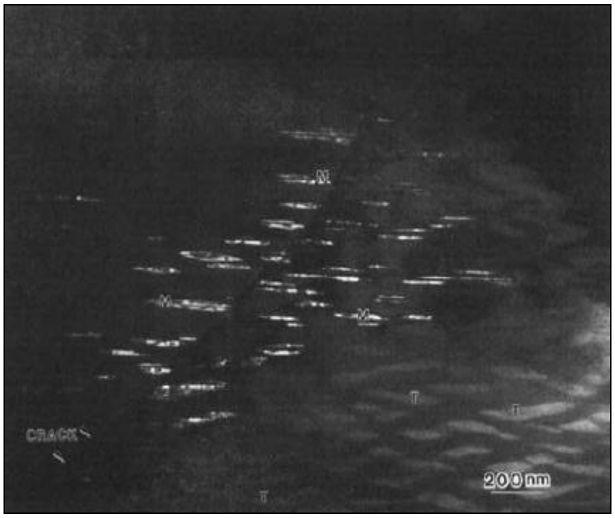

Fig 6: Transformation zone in thin foil of toughened ceramic.

The higher *K* level at which crack advance resumed could be associated either with the propagation of the amested crack or with the propagation of a nearby crack which appeared to nucleate, grow, and eventually link up with the main crack by a crack bridging process as shown in fig.7

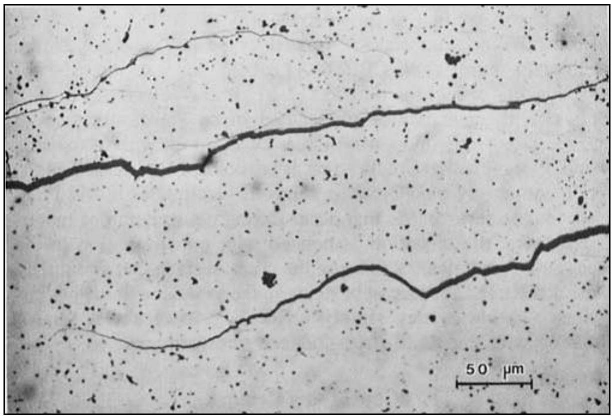

Fig 7: The lower crack arrested, and further loading caused nucleation of another crack about 100 um away.

6. (TTZ) Transformation-toughened zirconia

Transformation-toughened zirconia (or TZC, toughened zirconia ceramics) - the groups of ZrO2-matrix ceramics that encompass the PSZ and TZP systems [3].

7. (Ca-PSZ) Calcium-cation-doped Partially Stabilized Zirconia

Calcium-cation-doped PSZ-generally added as CaO in the range 7.5– 8.7 mol% CaO–ZrO2 and, for commercial alloys, 8.4 mol% (4.0 wt.%) has been most common [3].

8. (MPZ) Monoclinic polycrystalline zirconia

Monoclinic polycrystalline zirconia-an agglomerate of *m*-ZrO2 grains added to ceramic matrices to form, after suitable processing, microcrack-toughened, high-density refractories [3].

9. 3Y-TZP (yttrium-cation-doped tetragonal zirconia) (used in dentistry)

3Y-TZP is available in dentistry for the fabrication of dental crowns and fixed partial dentures. The restorations are processed either by soft machining of pre-sintered blanks followed by sintering at high temperature, or by hard machining of fully sintered blocks [7].

The mechanical properties of 3Y-TZP strongly depend on its grain size [8, 9]. Above a critical grain size, 3Y-TZP is less stable and more susceptible to spontaneous $t \rightarrow m$ transformation whereas smaller grain sizes (<1 μm) are associated with a lower transformation rate [10]. Moreover, below a certain grain size (0.2 μm), the transformation is not possible, leading to reduced fracture toughness [11]. Higher sintering temperatures and longer sintering times lead to larger grain size [12, 13]

10. Glass-infiltrated zirconia-toughened alumina (ZTA) (used in dentistry)

Another approach to advantageously utilize the stress-induced transformation capability of zirconia is to combine it with an alumina matrix, leading to a zirconia-toughened alumina (ZTA) [[14, 15]. These materials have recently received interest as potential bio ceramics [16, 17]. One commercially available dental product, In-Ceram® Zirconia® (Vident™, Brea, CA), was developed by adding 33 vol.% of 12 mol% ceria-stabilized zirconia (12Ce-TZP) to In-Ceram® Alumina® [18]. The microstructure of In-Ceram® Zirconia® is shown in Fig. 8, in which the zirconia grains appear brighter compared to the darker alumina grains. One of the advantages of the slip-cast technique is that there is very limited shrinkage. However, the amount of porosity is greater than that of sintered 3Y-TZP and comprises between 8 and 11% [19].

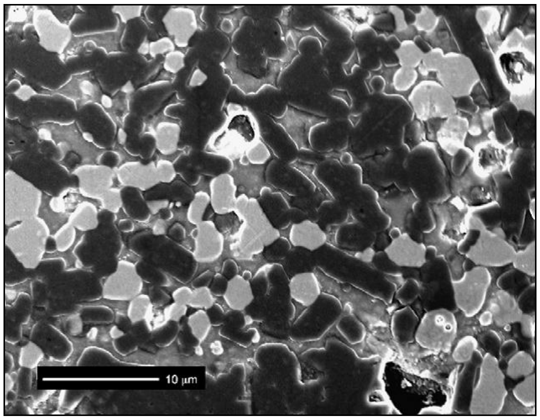

Fig 8: Scanning electron micrograph of In-Ceram® Zirconia® (Vident™, Brea, CA). Zirconia grains appear in brighter contrast compared to darker alumina grains.

Guazzato *et al*. reported a significantly higher flexural strength for In-Ceram® Zirconia® processed by slip-casting (630 ± 58 MPa) compared to the machined material (476 ± 50 MPa) [22]. In some of the newly developed ZTA for biomedical applications, excellent mechanical properties are obtained by promoting a fine and uniform dispersion of zirconia grains in an alumina matrix [23, 24]. such dispersion is readily obtained by sol–gel processing. An advancing crack triggers the $t \rightarrow m$ transformation. The associated increase in volume creates microcrack in the alumina matrix surrounding the transformed particle. The toughness is therefore enhanced by micro cracking [25].

Zirconia as dental implants

Combination of mechanical properties and excellent biocompatibility makes zirconia ceramic one of the best biomaterials for prosthetic joints, including hip joints. Zirconia may have better affinity to bone tissue than other biocompatible ceramics. The values of elastic modulus of zirconia are half that of single-crystal sapphire, which may contribute to biomechanical integration of the bone-implant interface.

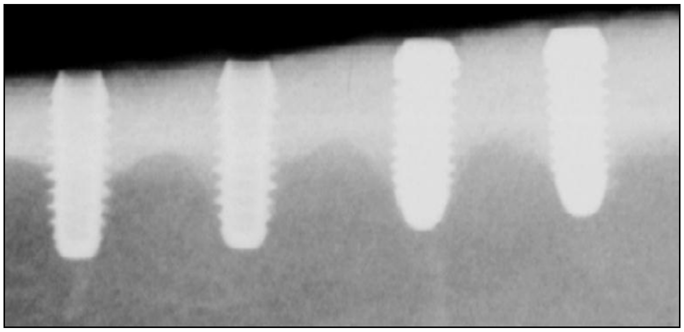

Fig 9

Radiograph showing titanium (left) and zirconia (right) implants inserted into the tibia of mini pigs after 12 weeks of healing time

The biocompatibility of zirconia ceramics was investigated *in vivo* by implanting them in bone and soft tissues; in zirconia implants inserted into subcutaneous tissue, only a small inflammatory cell infiltrate was found, and the implant was completely encapsulated by a thin fibrous connective tissue [6].

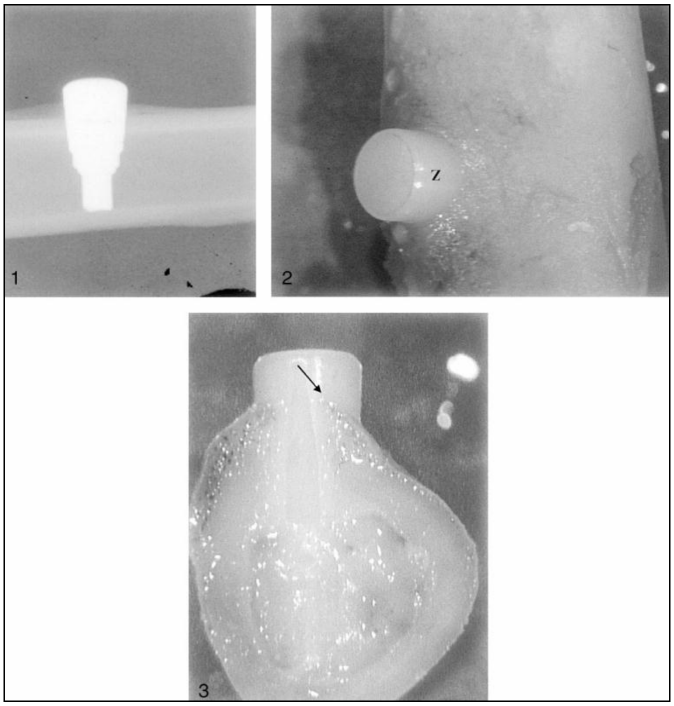

Fig10. 1: Radiography of a retrieved zirconia implant inserted in rabbit tibia. **2:** Zirconia implant (Z) inserted in rabbit tibia after removal of the surrounding soft tissues. **3:** Cut surface of the implant and bone: the bone (arrow) is closely adapted to the implant

6.1 Osteointegration of zirconia

Zirconia implants with modified surfaces display features of osseointegration similar to those of titanium implants. These results are promising in using zirconia implants for dental application in the future. (Fig 11 and 12)

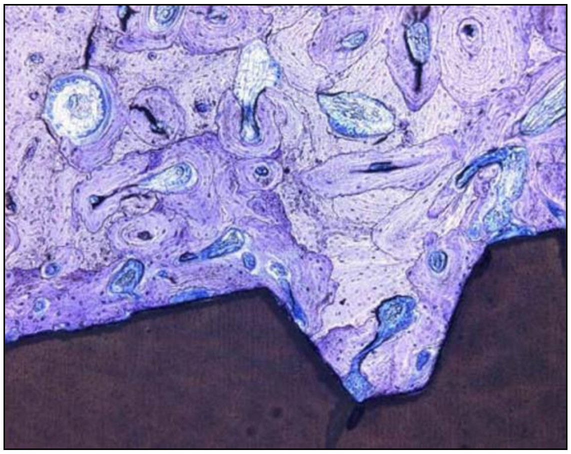

Fig 11

After 12 weeks of healing, mature lamellar bone is evident in intimate contact with the zirconia implant

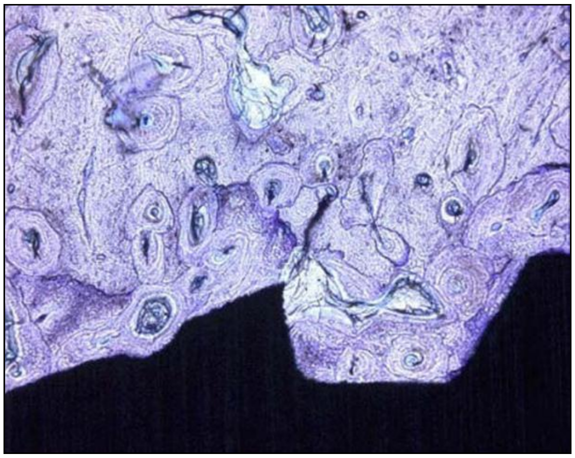

Fig 12: 12 weeks of healing titanium implant

Discussion

Zircon has been known as a gem since ancient times. The name zirconium comes from the Arabic "Zargun" (golden in color) which in turn comes from the two Persian words "Zar" (Gold) and "Gun" (Color). Zirconia is a crystalline dioxide of zirconium. A Zirconium oxide was first used for medical purposes in 1969 for orthopedic application. It was proposed as a new material for hip head replacement instead of titanium or alumina prostheses. Due to an increasing interest in esthetics and concerns about toxic and allergic reactions to certain alloys, patients and dentists have been looking for metal-free tooth-colored restorations. Therefore, the development of new high strength dental ceramics, which appear to be less brittle, less limited in their tensile strength, and less subject to time dependent stress failure, has dominated in the later part of 20th century. These capabilities are highly attractive in prosthetic dentistry, where strength and esthetics are paramount. It has become a popular alternative to alumina as biomaterial and is used in dental applications for fabricating endodontic posts, crown and bridge restorations and implant abutments. It has also been applied for the fabrication of esthetic orthodontic brackets. Toughening mechanisms which operate in many zirconia ceramics is the key issue for the use of these materials in structural and in biomedical applications.5It has recently been advocated by Lawn *et al*. that a stronger and tougher core material would improve the reliability and therefore the lifetime of an all ceramic crown. An improvement of the clinical performance of the restoration is also expected, if steps are taken to avoid the formation of flaws. Flaws may be introduced as a result of grinding and sandblasting, which are common stages of the fabrication and clinical adjustment of all-ceramic restorations [22]. The understanding and the improvement of ceramic materials properties needs a good control of processing and an understanding of its effect on microstructure. Thus a global approach to ceramics, including the effect of processing on microstructure and of microstructure on final properties, must be taken in order to extend the use of ceramic materials [23]. During the past few decades, new types of reinforced ceramic systems with improved mechanical core properties have been introduced. Clinically, these systems have been successfully employed in the fabrication of all-ceramic crowns and fixed partial dentures (FPDs). 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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