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A Review of Zirconia as a Dental Restorative Material

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Abstract: The development of dental crowns is highly concerned with optimum mechanical properties, superior esthetic appearance and biocompatibility. In order to meet these requirements, structural ceramics have been improved and have become increasingly more popular in dentistry. Among the dental ceramics, zirconia is the dental restorative material most commonly used in dental restoration. This material has unique characteristics, such as high fracture toughness, biocompatibility, and color approximating the natural tooth color. However, zirconia is too opaque, which reduces the esthetic appearance of the restoration. This paper reviews zirconia as a dental material with the potential for further use in ceramic dentistry.

Key words: Zirconia, Transformation toughening, Zirconia 3Y-TZP, Ceramic, Nanostructured zirconia.

INTRODUCTION

Zirconia (ZrO_2) is a ceramic first identified by the German chemist Martin Heinrich Klaproth in 1789. The first paper on the use of zirconia as a biomaterial was published by Helmer and Driskel in 1969. In recent years, the use of ceramic zirconia as a biomaterial for implants and dental crowns in dentistry has grown exponentially, because of the superior mechanical properties of zirconia, such as its high mechanical strength, as well as its good wear resistance and friction (Chevalier, 2006; Denry and Kelly, 2008). This has encouraged fellow researchers from the fields of orthopedics and dentistry to use zirconia as a biomaterial in their respective applications. The use of zirconia in orthopedics began more than 20 years ago (Chevalier and Gremillard, 2008). Meanwhile, in the field of dentistry, using zirconia in dental restoration applications has become a practice since 1998 (Glauser *et al*., 2004). The high strength of zirconia has encouraged its use for load bearing applications in dentistry such as dental crowns, fixed partial dentures (FPD) and dental implants (Kohal *et al.*, 2006).The difficulties of achieving good aesthetics with porcelain fused to metal (PFM) restorations and the desire for metal free solutions have resulted in the increased use of zirconia (Jang *et al.,* 2011).

The processing of dental ceramics employed in the development a dental restoration involves several techniques and technologies such as ceramming, slip casting, heat pressing or injection molding, and machining with Computer Aided Design and Computer Aided Manufacturing (CAD/CAM) technology. The pioneer of using CAD/CAM techniques for the fabrication of tooth restorations was Duret in the 1970s (Duret, 1988). Ten years later, the CEREC system was marketed by Siemens (now Sirona). Cercon from DeguDent was introduced in 1998. In 2001, Nobel Biocare unveiled Procera AllZircon (now Procera Zirconia), and In-Ceram YZ CUBES was introduced by VITA in 2004 (Ban, 2008). Figure 1 shows tooth crown fabricated from a presintered zirconia core (Cercon, Dentply). The presintered 3Y-TZP block was milled using CAD/CAM. The core was machined larger than the actual size to compensate for the shrinkage that occurs during sintering.

2. Zirconia as a Dental Material:

2.1 Microstructure Properties:

Zirconia is dioxide of zirconium. Zirconia has three possible crystal structures: monoclinic (M), cubic (C), and tetragonal (T). Zirconia naturally is in the monoclinic phase at room temperature and pressure. This material will transformed into the tetragonal phase whenever the temperature is increased incrementally to approximately 1170°C, and into the cubic phase at 2370°C (Piconi and Macauro, 1999). When stress is applied to zirconia, stress-induced phase transformation occurs, increasing its crack propagation resistance. This process involves the transformation of metastable tetragonal grains into the monoclinic phase at the crack tip. The transformation is accompanied by volumetric expansion, which induces compressive stresses that hinders crack propagation on the existing stress field (Garvie *et al*., 1975; Piconi and Macauro, 1999; Sergo and Lughi, 2010). Figure 2 represents the stress-induced toughening process. The addition of zirconia to metal oxides such as magnesium oxide (MgO), calcium oxide (CaO), and yttrium oxide (Y_2O_3) produces good molecular stability. This method willretain the tetragonal structure at room temperature thereby controlling the stress-induced tetragonal to monoclinic (T→M) transformation. This phenomenon

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willlimits crack propagation efficiently and leading to high fracture toughness (Piconi and Macauro, 1999).

2.2 Types of Zirconia Ceramics Available for Dental Applications:

Three types of zirconia have been widely used in dental applications, namely, magnesium partially stabilized zirconia (Mg-PSZ), zirconia-toughened alumina (ZTA), and the most commonly used 3Y-TZP zirconia (Denry and Kelly, 2008).

2.2.1 Magnesium Partially Stabilized Zirconia (Mg-PSZ):

Mg-PSZ is reportedly unsuitable for use in dentistry because of its high porosity and large grain size, which may lead to surface wear. The sintering temperature of this type of zirconia is also much higher than other composites, between 1680°C and 1800°C. Furthermore, Mg-PSZ has poor stability, which may slightly lower the energy for the T→M transformation (Piconi and Macauro, 1999).

2.2.2 Zirconia-Toughened Alumina (ZTA):

ZTA is a combination of zirconia with an alumina matrix, which undergoes stress-induced transformation to achieve excellent mechanical properties. Among the dental ceramics, the only ceramic product available in the market which is toughened ceramic through dispersion is the In-Ceram Zirconia (Vita Zahnfabrik, Germany). This product can be processed via slip-casting or milling at a pre-sintering stage (Denry and Kelly, 2008). However, ZTA has a large amount of pores, between 8% and 11% (Guazzato *et al*., 2003).

2.2.3 Zirconia 3Y-TZP:

Tetragonal zirconia polycrystals stabilized with 3 mol% 3Y-TZP zirconia has been utilized for dental applications, because the mechanical properties are similar to that of metal, whereas the color approximates that of natural teeth (Piconi and Macauro, 1999). To date, studies on the potential of 3Y-TZP zirconia in dental applications continues to increase. This statement is supported by journal publications on the 3Y-TZP zirconia in dental applications, which is increasing each year as shown in Figure 3. Therefore, more information and further detailed studies are needed to identify the capabilities of these materials as biomaterials.

3Y-TZP has better mechanical properties than the other zirconia-based materials. Like the polycrystal materials, 3Y-TZP shows low porosity and high density (Zarone *et al*., 2011). The critical grain size for the material is 1 µm, i.e., if the size exceeds 1 µm, then 3Y-TZP becomes prone to phase transformation toughening because of the lower stability. Meanwhile, if the grain size is smaller than 1 µm, this phenomenon does not occur. In addition, zirconia with grain size below 0.2 µm does not undergo this phase transformation toughening and its fracture toughness decreases (Cottom and Mayo, 1996). Grain size significantly influences the mechanical properties of zirconia 3Y-TZP, where high temperature and longer sintering periods produce larger grain sizes and will subsequently lower the mechanical properties (Chevalier *et al*. 2004). Higher sintering temperatures lead to larger grain sizes. Consequently, the sintering process becomes the determining factor, and the process control needs to be emphasized throughout the process of producing the dental restoration because it plays a part in grain size and simultaneously influences the mechanical properties and stability of the zirconia.

3. Clinical Aspects of Zirconia Restorations:

3.1 Mechanical Properties:

In the construction of dental restoration, esthetics in terms of a color and translucency, mechanical properties, and biocompatibility are mandatory (George and Eichmiller, 1995). The relevant mechanical properties are high flexural strength and fracture toughness. This means that the material has the ability to stop or limit crack propagation (Zarone *et al*., 2011). 3Y-TZP zirconia has high fracture strength and toughness compared with other dental ceramics when they come in a dense form. 3Y-TZP zirconia exhibits the highest fracture toughness compared with alumina and porcelain; 3Y-TZP zirconia has the highest critical stress intensity factor (KIC), between 6 $MPam^{1/2}$ to 11 $MPam^{1/2}$, which is more similar to that of metals than other materials (Piconi and Macauro, 1999; Denry and Kelly, 2008). The flexural strength of zirconia ranges from 800 MPa to 1000 MPa, which enables the material to accommodate cyclic stress (Garvie *et al*.,1975). Table 1 shows the type of zirconia-based all ceramic restoration commercially used in dental clinics (Ban, 2008). Most of the zirconia from Lava, Cercon, In-Ceram YZ CUBES, and Procera Zirconia Y-TZP possess high fracture toughness and reliable flexural strength. Thus, they can be formed using CAD/CAM technology.

3.2 Optical Properties:

One factor that cannot be overlooked in using zirconia as dental material is its similarity in to natural teeth. However, the drawback of zirconia ceramics should also be considered. Zirconia is an opaque ceramic, which limits its use (Spear and Holloway, 2008; Jiang *et al*., 2011). Zirconia-based dental restorative material is mainly used as a core material. Feldspathic porcelain is still needed for the veneers of zirconia-based restorative material and is only placed in the anterior region due to low mechanical stability and brittleness of porcelain (Conrad *et al*., 2007). Posterior placement needs to be done with caution, because the mechanical strength of that region is not enough to withstand the excessive load (Pjetursson *et al*., 2007).

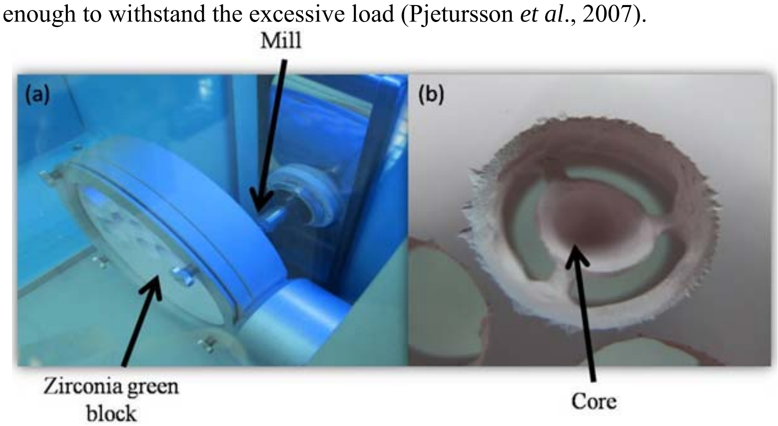

Fig. 1: Represent (a) milling process of zirconia Cercon; (b) core of zirconia Cercon.

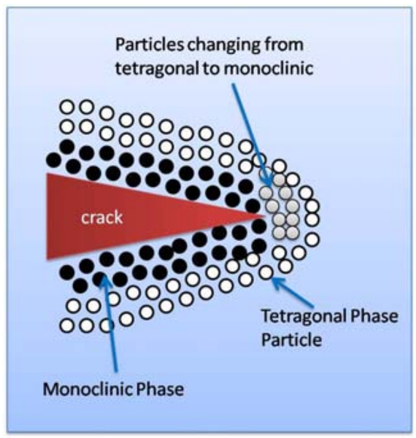

Fig. 2: Transformation toughening process of zirconia.

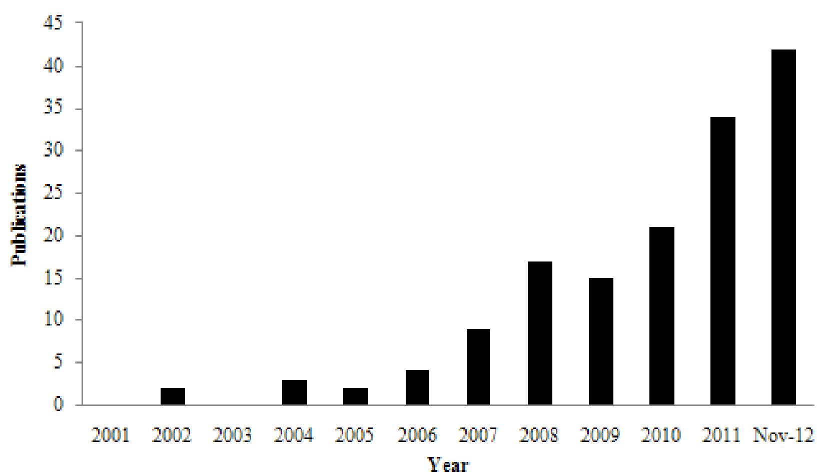

Fig. 3: Increased number of journal publications 3Y-TZP zirconia in dental applications (Keyword search "3Y-TZP zirconia in dental application" in http://www.sciencedirect.com, Nov 92012).

3.3 Biocompatibility:

Zirconia exhibits good biocompatibility. Since 1990, in vitro studies have been done to obtain tissue cell reactions against zirconia as a biomaterial. The in vitro studies confirmed that zirconia is non-cytotoxic and is safe to use for dental applications (Torricelli *et al*., 2001; Lohmann *et al*., 2002). Based on similar studies, the fatigue cycle of this type of zirconia is expected to have a lifespan of approximately more than 20 years in contrast to prosthesis from metal ceramics (Studart *et al*., 2007).

3.4 Low temperature degradation:

Low-temperature degradation (LTD) is a phenomenon wherein zirconia is exposed to various conditions in the oral cavity, such as exposure to aqueous saliva, temperature changes, acidification during food intake, and cyclic loading during chewing, all of which decreases its mechanical strength (Nguyen *et al*., 2009; Mitsias *et al*., 2010). This phenomenon is also known as hydrothermal degradation (Swab, 1991; Chevalier *et al*., 1999; Kelly and Denry, 2008). With LTD, the energy threshold for T→M transformation is reduced (Guo, 2004). Water penetration then worsens the transformation, and this leads to microcracking, grain pullout, and finally surface roughening (Kelly and Denry, 2008). Hydrothermal stability can be achieved in 3Y-TZP by adding alumina, which is homogeneously distributed in the zirconia matrix (Chevalier *et al*., 2004).

3.5. Nanostructured Zirconia:

Nanometer-sized particles have gained research interest in the past few decades because of properties of the material change drastically as the grain size approaches the nanometer scale (Sun and Gao, 2003). Nanoparticles have the capability to obstruct stress when under loading, thereby hindering crack propagation in semi-crystalline and amorphous polymers (Zhang and Kim, 2010). One advantage of the nanozirconia powder is that it attains a homogenous state at low sintering temperatures (Vasylkiv *et al*., 2004). Thus, the use of nanoscale zirconia is promoted. Furthermore, noted that at this particle size, higher mechanical strengths can be achieved (Sun and Gao, 2003). Some reviews reported that the structure of ceramic normally do not produce opacity, which inclines to have translucency. In addition, this translucency can be achieved based on several factors, including a very fine grain size within the submicron range, pore sizes less than 1%, and low porosity (Chevalier and Gremillard, 2009). Additionally, the ceramic compression of translucent TZP zirconia that meets the demands for high-mechanical-strength restorative application can be produced with grain sizes less than 0.5 µm.

Table 1: Mechanical properties of zirconia-based all ceramic restoration

Brand name	Manufacturer	Main composition	Forming method	Fracture Toughness (MPa $m^{1/2}$)	Flexural strength (MPa)
In-Ceram zirconia®	Vita	Porous Al_2O_3.Ce-ZrO_2 (33 wt%) + lanthanide glass	Glass infiltration	4.4	600
In-Ceram YZ CUBES®	Vita	Y-ZrO_2	CAD/CAM	5.9	900
Cercon®	DeguDent	Y-ZrO_2	CAD/CAM	9 -10	900 - 1200
Lava®	3M ESPE	Y-ZrO_2	CAD/CAM	10	1272
Procera Zirconia Y-TZP®	Nobel Biocare	Y-ZrO_2	CAD/CAM	10	1121

4. Conclusion:

The optical property of dental materials plays an important role in matching the ceramic restorations to the natural appearance of teeth. Zirconia ceramics are selected for the fabrication of dental restorations, it has a color similar to teeth but if translucency is needed then other ceramic materials should be considered. When compared to others all ceramic dental material, zirconia Y-TZP possess better mechanical properties due to its transformation toughening. However, a number of failures have been reported in the literature related to low-temperature degradation of zirconia. Caution is needed when interpreting the available survival data in the literature. The emergence of nanostructured zirconia can continue to improve the development of the dental restoration. The dental practitioner should be aware of this development and more research need to be done to explore the potential of this material as a dental restoration.

In summary, zirconia-based dental materials have the potential for use in constructing dental restoration applications and are recommended in clinical practice. Furthermore, the introduction of stabilized zirconia has created a real possibility and promise for the application of zirconia in dental reconstructions. Nevertheless, the challenge of developing zirconia-based dental material with superior esthetics and optimum mechanical properties with excellent biocompatibility remains.

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