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Zirconia in Dentistry: An Updated Review

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Abstract

Zirconia, a crystalline form of zirconium dioxide (ZrO_2), is known for its excellent mechanical, optical, and biocompatible characteristics. Increasingly, all-ceramic zirconia-based restorations are favored in modern restorative and prosthetic dentistry due to their aesthetic and biologic benefits. Over the years, dental zirconia has evolved significantly, resulting in a wide range of materials tailored for prosthetic use. However, current literature lacks a comprehensive, updated classification of these newer zirconia biomaterials. This review aims to bridge that gap by presenting an overview and classification of contemporary zirconia materials used in dentistry. The information compiled here will be valuable for dental professionals, technicians, prosthodontists, academic faculty, and researchers involved with zirconia in dental applications.

Subjects: Bioengineering, Dentistry

Keywords: Dental ceramics, Y-TZP, 3Y-TZP, 5Y-TZP, CAD/CAM, Translucency

Introduction

Zirconia (ZrO_2), a polymorphic oxide of zirconium, is valued in dentistry for its robust mechanical strength, appealing optical qualities, and biocompatibility (Bapat et al., 2022). It exists in three primary crystallographic phases: monoclinic, tetragonal, and cubic (Saridag et al., 2013; Bocanegra-Bernal & dela Torre, 2002). Metal-free restorations, particularly all-ceramic zirconia prostheses, have seen a surge in popularity due to their esthetic superiority and compatibility with oral tissues (Kongkiatkamon et al., 2021).

Recent advancements in digital dentistry, such as CAD/CAM technologies and intraoral scanning, have further streamlined the fabrication of zirconia restorations, enhancing their accuracy and workflow efficiency (Al-Qahtani et al., 2021; Ahmed et al., 2021).

At room temperature, pure zirconia stabilizes in the monoclinic phase but transforms into tetragonal at 1,170°C and eventually into cubic at 2,370°C. However, upon cooling, a reverse transformation back to monoclinic can occur, accompanied by a 5% volume

change that complicates sintering (Piconi & Maccauro, 1999). Zirconia ceramics are available in various forms: monolithic (monochromatic), polychromatic multilayer, and hybrid multilayered types.

A reliable bond between zirconia and tooth substrate is crucial for the durability of dental prostheses. Surface conditioning techniques, such as air abrasion with alumina particles followed by the use of MDP-based primers or cements, improve the bonding interface (Araújo et al., 2018; Melo et al., 2015; Silveira et al., 2022).

Despite several classifications available for earlier zirconia types (Ban, 2021; Güth et al., 2019), the literature lacks an up-to-date, comprehensive overview of the most recent zirconia biomaterials. This review attempts to fill that void and proposes a current classification scheme relevant to the dental profession.

Phases of Zirconia (Monoclinic, Tetragonal and Cubic)

At ambient temperature, pure zirconia predominantly exists in the monoclinic phase. When the temperature rises to approximately 1,170 °C or under conditions of low-temperature degradation (LTD), it transitions into the tetragonal phase (Ban, 2021). With further heating beyond 2,370 °C or during processes like hydrothermal aging, the material begins to revert to the monoclinic structure (Piconi & Maccauro, 1999; Sorrentino et al., 2019; Rekow et al., 2011). Upon cooling, the tetragonal phase returns to its monoclinic state. Stabilizing sintered zirconia ceramics poses challenges, primarily due to a volumetric shift of nearly 5% that occurs during the tetragonal-to-monoclinic phase transformation.

Zirconia Properties

- **Physical Properties**: Zirconia resists acid erosion and has low thermal conductivity. Its thermal expansion coefficient remains constant across yttria levels (Ban, 2021).
- **Mechanical Properties**: Zirconia ranks among the hardest dental materials. 3Y-TZP has a flexural strength of ~584 MPa, while 5Y-TZP averages ~373 MPa (Liao et al., 2023). Surface aging through pH-cycling or autoclaving increases monoclinic content and reduces strength (Flinn et al., 2012).
- **Optical Properties**: Higher yttria content increases translucency but lowers mechanical strength. 5Y-TZP is suitable for anterior crowns and veneers, while 3Y-TZP is preferred for load-bearing bridges (Ban, 2021; Jitwirachot et al., 2022).
- **Biological Properties**: Zirconia shows excellent tissue compatibility and minimal cytotoxicity or genotoxicity. Its surface can be engineered for optimal protein absorption and fibroblast adhesion (Christel et al., 1989; Kim et al., 2015; Scarano et al., 2004). It attracts fewer bacteria than titanium, contributing to better periodontal health.

Zirconia Classification

Earlier classifications were based on generation and stabilization techniques (e.g., PSZ, TZP). Today, zirconia materials can be categorized by:

- **Yttria content** (3Y, 4Y, 5Y, 6Y)
- **Composition** (uniform vs hybrid)
- **Color layers** (monochromatic vs polychromatic)
- **Layering** (monolayer vs multilayer)

Yttria-Stabilized Zirconia

To stabilize zirconia at ambient conditions, oxides such as yttria (Y_2O_3), ceria (CeO_2), calcium (CaO), and magnesium (MgO) are incorporated (Piconi & Maccauro, 1999). Among these, yttria is most commonly used to stabilize the tetragonal structure (Leib et al., 2015). However, under aging or low-temperature degradation (LTD), yttria content diminishes, triggering a

transformation to the monoclinic phase (Rekow et al., 2011).

Yttria doping not only stabilizes the crystalline structure but also enhances thermal resistance. Based on yttria content, zirconia is categorized into various forms, such as 3Y-TZP, 4Y-TZP, 5Y-TZP, and 6Y-TZP (Zhang, 2014).

- **3Y-TZP** (3 mol% yttria) offers superior strength but limited translucency.
- **5Y-TZP** (5 mol%) is more translucent but has compromised strength.
- Zirconia with 8+ mol% yttria forms cubic stabilized zirconia (CSZ), while 3–8 mol% yields partially stabilized zirconia (PSZ).
- Multilayer types such as M3Y (high translucency) and M6Y (ultra-high translucency) have also emerged.

Under microscopy, 3Y-TZP shows finer grain structures. Mechanical testing confirms that 5Y-PSZ is less durable, whereas 3Y and 4Y variants exhibit comparable fatigue resistance (Ban, 2021; Harada et al., 2020).

Sintering of Zirconia

Sintering strengthens zirconia by densifying its crystalline structure. Regular sintering tends to produce greater grain sizes and translucency compared to speed sintering. Studies indicate that fast sintering can improve flexural strength due to structural changes, although it may reduce translucency (Juntavee & Attashu, 2018; Liu et al., 2022b).

Surface Modification and Adhesion

Zirconia's chemical inertness poses challenges for bonding. Surface treatments—air abrasion and tribochemical silica coating—enhance micromechanical retention. MDP-based cements are commonly used for improved adhesion. While traditional zirconia bonding is well-documented, more research is needed on the new translucent generations (Scaminaci Russo et al., 2019; Aung et al., 2019).

Uses of Zirconia in Dentistry

1. Single tooth restoration
2. Fixed dental prosthesis
3. Posts
4. Implants
5. Implant abutments

Zirconia Crowns & Bridges

The criteria for selecting cases for zirconia crown restorations—such as limited interocclusal space, parafunctional habits, malocclusion, short clinical crowns, tooth mobility, and inclination—are similar to those used for other types of all-ceramic crowns. In clinical practice, once milling is complete, a consistent zirconia core with a thickness of 0.5 mm is typically recommended for single posterior crowns. In anterior regions, where aesthetics and strength requirements may differ, it is possible to fabricate copings as thin as 0.3 mm. However, reducing the coping thickness from 0.5 mm to 0.3 mm can compromise the crown's resistance to fracture. FPDs fabricated with the CAD/CAM system exhibit smaller marginal discrepancy values than those fabricated with the CAM-only system. Beuer et al. reported the complex fabrication process and variability of manual procedures for the CAM-only system, such as definitive die preparation with a spacer, and stated that waxing and wax pattern removal from the die might cause differences in adaptation. In terms of the state of zirconia at milling, four-unit FPDs made from fully sintered zirconia have been reported to show significantly better marginal adaptation than FPDs made from pre-sintered zirconia.

Zirconia Posts

Zirconia posts were initially introduced by Meyenberg, who noted that their flexural strength—ranging between

900 and 1200 MPa—was comparable to that of cast gold and titanium posts, and that they could be fabricated in similar dimensions to those metals. Today, zirconia is extensively used in prosthodontics due to its excellent chemical stability, superior mechanical strength, high fracture toughness, and a Young's Modulus comparable to stainless steel alloys. Despite these advantages, zirconia posts have limitations—particularly in situations requiring post removal for retreatment. Because of their extreme hardness and rigidity, zirconia posts are nearly impossible to remove once cemented within the root canal. While grinding them away is unfeasible, attempts to extract fractured zirconia posts using ultrasonic methods can lead to a significant temperature increase in both the post and the surrounding root surface. Additionally, the inherent stiffness of zirconia poses another drawback, as ideally, a post should fail or lose retention under intraoral stress before causing a root fracture.

Zirconia Implants

Zirconia implants have gained significant interest in dental implantology, primarily because of their distinctive combination of high mechanical strength, biocompatibility, and favorable esthetic properties. Tetragonal zirconia polycrystalline (YTZP) materials along with yttria stabilization have remarkable corrosion resistance along with wear resistance in addition to high flexural strength contrary to other dental ceramics[8]. When the compressive load capacity of zirconia implants based on blade type was evaluated, it was discovered to be sufficient for occlusion[9]. Zirconia's unloaded fracture strength (512.9 N) was noted to be greater compared to its loaded fracture strength (401.7 N)[10]. The metastable tetragonal structure may be maintained at normal temperature by alloying unadulterated zirconia along with stabilizing oxides such as calcium oxide, magnesium oxide, and yttrium oxide [10].

Zirconia has been inorporated into dental implant abutments due to its superior fracture resistance when compared to alumina and other ceramic materials. It demonstrates a strong affinity for bone, with the bone-to-implant interface showing characteristics comparable to those of titanium implants. Zirconia abutments offer reliable support for implant-retained restorations, particularly in the anterior and premolar regions. They are especially beneficial in cases where soft tissue height is minimal. Additionally, zirconia reduces the risk of gray discoloration in the peri-implant tissues, a common issue with metal components.

The application of zirconia frameworks in implant-supported prostheses facilitates the creation of aesthetically pleasing outcomes using standard ceramic layering techniques. Since there is no need to mask the dark color of metal alloys like cast or milled titanium, it becomes easier to achieve lifelike, translucent restorations—especially in lighter shade ranges—with greater predictability and visual appeal.

Biocompatibility of zirconia implants

The biocompatibility of zirconia was examined using a variety of in vitro experiments on osteoblasts, fibroblasts, lymphocytes, and monocytes, along with macrophages. Because zirconia has no immunosuppressed cytotoxic effects on osteoblasts, the cells can elaborate the extracellular matrix by synthesizing a wide range of various essential and structural proteins. According to Liagre et al.[11], zirconia does not cause any inflammatory pathways to arise. Zirconia is biocompatible because it does not possess a pseudo-teratogenic effect [12].

Zirconia underwent biocompatibility studies in vivo as well, and it was observed that after being implanted in soft tissue, it established a thin coating identical to the

layer of fibrous tissue in the instance with alumina[13].Lesser plaque accumulation has been reported with zirconia implants. Bacteria such as S sanguis, Porphyromonas gingivalis, short rods, and cocci have shown lesser adherence to zirconia than to titanium surface. The adhesion of Streptococcus to zirconia has also been shown to similar to that to glass ceramics. There seems to be no difference between polished and glazed zirconia as far as adherence of bacteria is concerned.

Zirconia wear products did not trigger any cytotoxicity in the soft tissue either. The results of a study that implanted pellets of solidified zirconia with 6% Y2O3 into monkey femurs revealed that zirconia is biocompatible with hard tissue when evaluated in vivo[14]. The proliferation of cells near zirconia was shown to be equivalent to titanium in the study by Kohal et al., although zirconia's surface modification was found to be more effective and failed to demonstrate osseointegration improvement[15].

Innovative computer-aided design and computer-aided manufacturing techniques

The development of computer-aided design and computer-aided manufacturing (CAD/CAM) has significantly transformed the production of zirconia biomaterials, leading to greater precision, customization, and efficiency. These digital technologies enable the creation of highly accurate, patient-specific restorations. Furthermore, advancements in digital workflows, along with innovations in software and hardware, have reshaped modern implantology. This progress has had a profound impact on the design, fabrication, and clinical performance of zirconia-based implants.

Cumulative case studies and emerging trends have analyzed the transformative role of innovative contemporary CAD/CAM techniques in optimizing zirconia implants for enhanced patient care [21].

Digital Scanning

In CAD/CAM systems, digital scanners create high-resolution 3D models of patients' dental structures, facilitating accurate customizations and implant planning and introducing the advancements in digital impression techniques, intraoral scanners, and their role in capturing precise data for designing zirconia implant restorations which signifies exploring their innovative applications in zirconia biomaterials and substantiate the significance of CAD/CAM techniques in implantology [22].

Computer-Aided Design

CAD software allows dental professionals to design patient-specific zirconia implants and restorations, tailoring them to match the individual's anatomy and requirements. CAD/CAM techniques expedite and facilitate zirconia's customization abutments and restorations, optimizing fit and esthetics and highlighting the advantage of patient-specific prosthetics [22].

Computer-Aided Manufacturing

The CAM process utilizes milling or 3D-printing techniques to produce zirconia-based dental components directly from digital designs. Milling machines employ diamond-coated tools to carve out the zirconia blocks, while 3D printing involves layer-by-layer additive manufacturing. Ingenious 3D printing techniques enable the fabrication of zirconia implant components with unprecedented precision. Future directions and challenges outline potential future directions, including artificial intelligence (AI)-driven design, bioprinting, and teledentistry and provocation accompanying with adoption and advancing CAD/CAM technologies in zirconia implantology [22].

High-Speed Sintering

An emerging CAM method, high-speed sintering (HSS) uses a combination of inkjet printing and rapid sintering to produce fully dense zirconia components in

significantly reduced timeframes. To revolutionize the manufacturing of zirconia biomaterials for dental implantology for enhanced patient care HSS has emerged as a cutting-edge manufacturing technology [19]. The principle of HSS is to achieve rapid and precise sintering of zirconia materials and offers several advantages such as reduced processing times, the ability to produce complex geometries, and energy efficiency that states the benefits of HSS in the context of zirconia implant manufacturing. HSS acknowledges well-structured fabrication of patient-specific zirconia implants and customization and enables the production of customized implant solutions [19].

Conventional Sintering

Traditional sintering is typically performed in a high-temperature furnace under controlled conditions to achieve adequate particle bonding and densification. Microwave sintering is an innovative sintering method that utilizes microwave energy to achieve rapid and uniform heating, reducing processing time and energy consumption [23].

Hot Isostatic Pressing

Hot isostatic pressing (HIP) is a post-sintering treatment that involves applying high pressure and temperature to further enhance the material's density and mechanical properties. HIP enhances the reliability and quality of zirconia implants and its potential for improving patient outcomes to achieve densification and eliminate defects in zirconia materials [19]. HIP-induced microstructural modifications influence zirconia's behavior, including grain size, phase transformations, and porosity reduction, and have been linked to improved biocompatibility of zirconia. The application of bioactive coatings to improve zirconia implant surface properties delves into how HIP can integrate surface modifications. To underscore the advantages of HIP comparative examination between HIP and conventional zirconia processing techniques, such as uniaxial pressing and isostatic pressing without heating, has been presented [19].

Glazing and Surface Modifications

Applying glaze or surface treatments to zirconia restorations enhances aesthetics, reduces wear on opposing dentition, and optimizes soft tissue response. For understanding the significance and principles of glazing zirconia surfaces, the composition of glaze materials, firing techniques, and the resulting changes in the implant's surface properties are important. Surface modifications play a pivotal role in optimizing zirconia biomaterials for dental implantology and significantly influence the roughness and topography of zirconia implants and explores how glazing makes a difference to these surface characteristics and its inference for soft tissue attachment as well as bacterial adhesion. The impact of glazing on zirconia's biocompatibility plays a pivotal role in promoting osseointegration demonstrating improved bone response [24].

Clinical applications of zirconia in dental implantology

Dental implantology has undergone significant advancements, and zirconia has played a pivotal role in revolutionizing restorative dental procedures such as single-tooth zirconia implants which have gained considerable attention for single-tooth replacements due to their excellent biocompatibility, mechanical strength, and aesthetic appeal. Moreover, partial and full arch implant-supported prostheses offer a durable and aesthetically pleasing solution for restoring multiple missing teeth. In addition to this, zirconia abutments and restorations provide an alternative to conventional metal-based restorations and discuss the advantages of zirconia abutments, including reduced soft tissue discoloration

and improved gingival health, as well as evaluate their clinical performance [24].

Future perspectives and advancements

Advancements in zirconia materials, manufacturing techniques, and surface modifications present exciting opportunities for further improving clinical outcomes. This section explores potential future developments and their implications for zirconia's clinical applications in dental implantology [25]. Recent research has emphasized the growing significance of zirconia-based nanomaterials and their applications in implantology which have emphasized the development of nanoscale modifications of zirconia which may amplify osseointegration as well as soft tissue integration. In addition to this, bioactive surface modifications explore the latest advancements in zirconia surface treatments, such as bioglass and hydroxyapatite coatings, and their potential clinical impact. 3D printing and customization are revolutionizing and offering unparalleled customization for the precise fabrication of patient-specific zirconia implants and restorations [26]. In optimizing zirconia implant placement, advancements in multimodal imaging, including cone-beam computed tomography along with intraoral scanning, are enhancing the accuracy of treatment planning and guided surgery. Some hybrid materials such as a combination of zirconia with other biocompatible substances may offer enhanced properties and versatility [26].

Conclusions

Zirconia has undoubtedly revolutionized the dental implantology landscape, offering remarkable mechanical properties, biocompatibility, and aesthetic appeal. .Modern zirconia materials vary based on yttria concentration, microstructural composition, and layering design. A higher yttria content improves aesthetics through increased translucency but compromises strength. Choosing the appropriate zirconia type depends on the clinical requirements—strength for posterior restorations or translucency for anterior aesthetics. Zirconia has emerged as a versatile as well as promising biomaterial in dental implantology, offering an exceptionally comprehensive understanding of zirconia's role in dental implantology, despite the challenges and complications that may arise.

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