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Assessment of the Mechanical Properties of 3D-printed Zirconia Utilized in Prosthetic Dentistry

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A B S T R A C T

Given its exceptional mechanical properties, aesthetic appeal, and biocompatibility, zirconia has found widespread application in prosthetic dentistry. Ceramic additive manufacturing (AM) has emerged as a promising avenue for creating intricate medical devices, particularly personalized ones, leveraging zirconia's potential to fabricate advanced configurations efficiently. AM zirconia unlocks numerous possibilities previously unattainable with conventional methods due to its versatility and effectiveness. This review delves into the physical and adhesive properties, precision, biocompatibility, and clinical applications of AM zirconia. Specifically, we emphasize its precision and biocompatibility, while also addressing current challenges and forecasting the future development and enhancement of AM zirconia. In essence, this review outlines the essential characteristics of AM zirconia materials for dental medicine and lays a foundational understanding for using 3D-printed zirconia in prosthetic dentistry.

Keywords: zirconia, prosthetic dentistry, additive manufacturing, 3D – printing, CAD/CAM.

1. Introduction

Yttria-stabilized tetragonal zirconia polycrystal (Y-TZP) is one of the most resilient ceramic materials currently available, primarily due to its exceptional mechanical properties, biocompatibility, and corrosion resistance [1,2]. However, the manufacturing of ceramics with specific properties and intricate geometries remains costly and inefficient [3]. Traditional methods of zirconia processing typically involve subtractive manufacturing (SM), which still presents limitations in its application. CAD-CAM subtractive manufacturing, in particular, results in significant raw material wastage, leading to reduced production efficiency [4]. Additionally, milling and post-processing steps, such as surface treatments, can introduce microcracks into the material, compromising the mechanical properties of the final products [5]. Moreover, SM struggles to meet the personalized needs of patients, especially with the growing demand for biocompatible solutions. These challenges have prompted researchers to explore alternative approaches for fabricating zirconia materials.

The concept of three-dimensional (3D) printing was introduced by Charles W. Hull in 1986, marking the beginning of a rapid expansion of this technology within industrial settings over the past four decades [6]. In 2000, stereolithography enabled the production of ceramic parts, marking an important milestone in 3D printing technology [7]. In dentistry, the fabrication of zirconia dental prostheses via direct inkjet printing was pioneered in 2009 [8], followed by the creation of the first metal mandible in 2011 [9]. Subsequent advancements included the manufacturing of root analog implants for immediate implantation in 2012 [14]. Lithography-based Ceramic Manufacturing (LCM) processes, such as those employed by Lithoz (Vienna, Austria), have provided state-of-the-art methods tailored specifically for dental zirconia applications. Notably, crowns for mandibular molars have been successfully produced using Lithoz's LCM technology [10].

The use of additive manufacturing (AM) has expanded across various fields, including dentistry and personalized medicine [11]. Additive manufacturing technologies such as fused deposition modeling, stereolithography (SLA), selective laser sintering, photopolymer jetting, inkjet printing, and powder binder printing are commonly employed [12]. A diverse range of materials, including composites, polymers, metal alloys, and ceramics, are utilized in additive manufacturing processes [13]. With a focus on achieving more customized restorations, including multi-material and multi-shade/translucency options, 3D printing is gaining popularity [14]. However, the development of 3D-printed zirconia dental materials is still relatively new, and many researchers are investigating their performance compared to CAD/CAM methods. It is crucial to assess whether these materials can be widely adopted in oral medicine and various clinical applications. Despite increasing research attention on the characteristics of AM dental zirconia materials, a comprehensive evaluation of AM zirconia remains lacking.

This review provides a comprehensive overview of the latest advancements in additive manufacturing (AM) dental zirconia materials. It discusses four main areas: the physical and adhesive properties, accuracy and biocompatibility of AM zirconia materials, their clinical applications, challenges, optimization methods, and prospects. The goal is to offer guidance and foundational knowledge for future research endeavors aimed at developing new material types. Additionally, it aims to assist clinicians in making informed decisions regarding the selection of materials for dental applications.

2. Materials and methods

The method involved implementing a search strategy that defined criteria for including and excluding studies, retrieving relevant literature, selecting appropriate studies, extracting relevant data, and organizing this data into tables to present outcomes concisely. Searches were performed across PubMed, Scopus, and Embase databases to gather literature published between 2002 and 2024.

The search terms used included variations related to zirconia restorations, 3D printing, CAD/CAM technology, milling, digital prosthetics, and additive manufacturing. s identified through the database searches underwent individual assessment by four reviewers, with any discrepancies in selection resolved through discussion until a consensus was reached.

3. Results

Multiple experiments have been undertaken to assess the mechanical characteristics of 3D-printed zirconia. Vickers hardness, which gauges material strength and resilience, indicative of its durability, has been a focal point. Experimental findings revealed that the Vickers hardness of 3D printed zirconia materials can reach up to 13.4 ± 0.2 GPa. Researchers examined both apparent hardness and true hardness utilizing proportional specimen resistance (PSR) and modified proportional specimen resistance (MPSR) models. It was evident that the hardness outcomes varied with the applied load. Comparatively, both the apparent and true hardness of 3D printed materials were lower than those produced through milling processes. Notably, Vickers hardness was influenced by pore size and porosity, factors that were carefully observed throughout the experiment [15].

Another extensively assessed mechanical property is flexural strength. The average bending strength of additive manufacturing (AM) ceramics meets the level 5 standard outlined in ISO 6872 (> 800 MPa). Despite the lower Weibull modulus of zirconia produced via digital light processing (DLP) compared to computer-aided design/computer-aided manufacturing (CAD/CAM) zirconia, as demonstrated by uniaxial (three-point bending) and biaxial (ring on ring) tests, studies have shown that zirconia specimens exhibit favorable flexural strength close to that of conventional CAD/CAM ones [3,11]. Moreover, certain studies have reported higher flexural strength achieved by 3D printing compared to CAD/CAM methods. While milled zirconia blocks demonstrate greater resistance to uniaxial compression than 3D printed blocks, 3D printed samples without fractures exhibit intriguing characteristics such as superior elastic modulus and lower compression deformation tendencies compared to milled samples [10].

Understanding the potential modes of failure of a prosthesis is crucial for optimizing dental ceramics. Dental zirconia, like all ceramic materials, is susceptible to brittle fracture resulting from flaws that may manifest during processing or usage. These flaws are distributed throughout the material in various sizes and shapes, typically being quite small [4]. Most studies have found no significant difference in fracture toughness between 3D printed and CAD/CAM zirconia components. However, some experimental findings have suggested that 3D-printed zirconia may exhibit lower fracture toughness than CAD/CAM counterparts. Additionally, studies have indicated that zirconia toughened with alumina possesses higher fracture toughness compared to zirconia alone [7, 12].

Studies have explored the impact of aging on the mechanical properties of 3D-printed zirconia materials. It was found that the m-phase content increased with aging time for both stereolithography (SLA) and digital light processing (DLP), yet the mechanical properties did not notably decrease. This suggests the stability of both materials [16]. Additionally, research conducted in a chewing simulator with cyclic temperature fluctuations between 5 and 55 °C for 5 million cycles in water revealed no significant difference in bending moment fatigue, indicating the long-term durability of additive manufacturing (AM) implants. However, implants exhibited substantially larger fracture stress and bending moment during mechanical fatigue in water at 90 °C. Moreover, when mechanical wear and tear in a chewing simulator with water at 90 °C were combined, 31 % tetragonal zirconia (t-ZrO_2) at the surface underwent tetragonal-to-monoclinic phase change, including wear and aging [2,14].

In general, factors such as solid content, printing parameters, debinding, and sintering procedures significantly influence the performance of final products. Higher solid content typically correlates with better mechanical performance. Researchers observed notable differences in indentation fracture resistance with varying building orientations. Specifically, performance improved when layer line orientations were inclined at 45° to the indentation direction. Poor temperature control during the sintering process can lead to high porosity in the product [9].

4. Discussion

This review provides a comprehensive overview of the latest advancements in additive manufacturing (AM) dental zirconia materials. It covers four main areas: the physical and adhesive properties, accuracy and biocompatibility of AM zirconia materials, their clinical applications, and the challenges and optimization methods associated with AM zirconia. Additionally, it discusses the prospects of AM zirconia.

To assess the accuracy of 3D printed crowns, researchers divided dental crowns into inner and outer surfaces, with a specific focus on examining the characteristics of the inner surface and the thickness and corresponding volume of the cement space. The crown was further divided into three parts: marginal, axial, and occlusal areas in the axial orientation. Visible-light scanning and micro-CT were employed to acquire three-dimensional data, which were then compared with the original CAD design. This process facilitated the evaluation of volumetric cement space, surface quality, manufacturing defects, and crown preparation adaptation [5, 17].

A study suggested that the occlusal region of the intaglio is likely to exhibit suboptimal trueness and crown adaptation for both subtractive manufacturing (SM) and additive manufacturing (AM) techniques when producing monolithic zirconia crowns. Consequently, the marginal area of the intaglio could be the decisive factor distinguishing between 3D printing and milling. Researchers conducted simultaneous comparisons between milled and 3D-printed crowns. While the intaglio occlusal surface, intaglio surface, and marginal area yielded differing outcomes, the printing group demonstrated superior accuracy in terms of the external surface of the crown compared to the CAD/CAM group. However, none of these findings indicated statistically significant differences [18]. Conversely, conflicting results have been reported, suggesting that the accuracy of AM full-contour crowns was lower than that of SM only in the marginal regions. Additionally, splint zirconia crowns, which consist of two pieces, have been evaluated for their ability to mimic the structure of enamel and dentin. It was found that the trueness of both the CAD/CAM group and the AM splint zirconia group was clinically acceptable, unlike the AM zirconia group [6, 8].

Understanding the precision of fabrication, including both systematic and random errors, as well as potential constraints affecting proposed and realized restorations, is paramount. Additionally, the choice of printing technique and parameters can significantly impact the outcome. Studies have indicated that reducing the layer height can enhance the accuracy of the final product, potentially attributed to the surface stepping phenomenon inherent in the additive manufacturing (AM) process [2,19]. Similar findings were observed in experiments involving four-unit bridges, with researchers emphasizing that the accuracy of digital light processing (DLP) was inferior to that of stereolithography (SLA). Moreover, the accuracy varies depending on the porosity level, which underscores the importance of considering porosity during manufacturing and adjusting it through sintering processes. Research has demonstrated that employing specially designed porous polymer molds can enable the accurate shaping of 3D-printed flexible products to a specific curvature. Various models and methods can be utilized to predict sample shrinkage, aiding in better control over the fabrication process. Additionally, both tooth types and the construction angle can influence the accuracy of the products [20].

5. Conclusions

The clinical implementation of additive manufacturing (AM) zirconia will be viable once the challenges are addressed. Achieving the desired outcomes in dental materials necessitates further exploration of efficient and manageable AM workflow techniques. Furthermore, conducting additional clinical studies on the accuracy and mechanical properties of AM zirconia materials is imperative.

Conflict of interest

The authors declared no potential conflicts of interest concerning the research, authorship, and publication of this.

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