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PHYSICAL, MECHANICAL, AND AESTHETIC PROPERTIES OF 3D PRINTED ZIRCONIA CROWNS A LITERATURE REVIEW

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ABSTRACT

3D printing technology has emerged as a transformative force in various fields, including dentistry. Among the advanced materials used in dental restorations, zirconia stands out due to its exceptional physical, mechanical, and aesthetic properties. This literature review examines the recent advancements in 3D-printed zirconia crowns, offering a detailed analysis of their physical, mechanical, and aesthetic characteristics. The review explores various additive manufacturing techniques such as stereolithography (SLA), digital light processing (DLP), binder jetting, and selective laser sintering (SLS), highlighting their influence on the properties of zirconia crowns. Studies indicate that 3D-printed zirconia crowns exhibit comparable, if not superior, physical properties, such as density and surface roughness, to those produced by traditional milling methods. Additionally, the mechanical properties, including fracture toughness, flexural strength, hardness, and wear resistance, are found to be on par with or better than milled crowns. Aesthetic aspects, such as translucency, color stability, surface finish, and polishability, also show significant improvements with 3D printing. The review further discusses the clinical performance, patient satisfaction, manufacturing processes, and cost implications of adopting 3D printing technology in zirconia crown production. The integration of this technology holds significant promise for enhancing dental restoration outcomes, offering precise, strong, and aesthetically pleasing solutions.

KEYWORDS: 3D Printed Zirconia Crowns , 3D printing ,Physical, Mechanical, and Aesthetic Properties

AIM OF THE STUDY

The aim of this study is to comprehensively review and analyze the current state of 3D-printed zirconia crowns, focusing on their physical, mechanical, and aesthetic properties. The study seeks to compare these properties with those of conventionally milled zirconia crowns and explore the potential benefits and limitations of using 3D printing technology in dental restorations. The study also aims to highlight future directions and potential improvements in materials, techniques, and clinical applications to maximize the benefits of 3D printing technology in dentistry.

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MATERIALS AND METHODS

The search strategy for this literature review involved a systematic and comprehensive approach to identify relevant studies and articles on the physical, mechanical, and aesthetic properties of 3D-printed zirconia crowns. The databases used for the search included PubMed, Scopus, and Google Scholar. Studies were selected based on relevance to the topic and publication in peer- reviewed journals. The review included various research formats such as in vitro studies, systematic reviews, literature-based reviews, and clinical trials. Out of 75 articles initially identified, 20 were found to meet the inclusion criteria.

The selected studies were classified into the following categories:

- **In vitro studies (n = 6)**: These studies examined the physio mechanical properties and surface characteristics of 3D-printed zirconia, including its fit, precision, and trueness in comparison to conventionally milled zirconia crowns .
- **Systematic reviews (n = 4)**: Comprehensive reviews, some including meta-analyses, were included to assess the trueness, precision, accuracy, biological, and aesthetic aspects of 3D-printed zirconia crowns in dental clinical applications .
- **Review articles (n = 7)**: These articles provided critical evaluations of the available research on zirconia as a dental material, focusing on its physical and mechanical properties, as well as advancements in 3D printing technology and CAD/CAM systems in dentistry .
- **Literature-based reviews (n = 2)**: These reviews summarized the current status and emerging applications of additive manufacturing technologies in dentistry, with a focus on polymer processing and dental prostheses .
- **Clinical studies (n = 1)**: A single clinical study evaluated the performance of high- translucent zirconia fixed dental prostheses using a digital workflow over a 6-year period.

INTRODUCTION

The integration of 3D printing technology, also known as additive manufacturing, has revolutionized many industries, particularly healthcare and dentistry. In the dental field, 3D printing allows for the efficient fabrication of customized dental restorations, such as crowns, bridges, implants, and dentures, with greater precision and less waste compared to traditional methods [1].

Zirconia (zirconium dioxide, ZrO^2) has gained significant attention in dental applications due to its combination of mechanical strength, fracture toughness, and biocompatibility [2, 3].

Traditionally, dental restorations made of zirconia were produced through subtractive manufacturing techniques, such as computer-aided design/ computer-aided manufacturing (CAD/CAM) milling from pre-sintered zirconia blocks [4,5]. While this method is effective, it is also associated with material wastage and limitations in producing highly intricate designs [6].

3D printing offers an alternative that reduces waste by precisely depositing material only where it is needed, layer by layer [7,8]. The flexibility of 3D printing allows for the creation of complex geometry and patient-specific restorations that better fit the patient's anatomy, leading to enhanced comfort and accuracy[9,10].

A key benefit of incorporating 3D printing in dentistry is its ability to integrate seamlessly with digital workflows, starting from intraoral scanning to the final restoration[1,6]. This integration not only enhances precision but also minimizes errors associated with manual intervention. In particular, the use of advanced 3D printing techniques, such as stereolithography (SLA) and digital light processing (DLP), has been instrumental in improving the quality of zirconia crowns by allowing for fine resolution and accurate reproduction of complex geometries [6, 7]. These methods have made it possible to fabricate restorations with superior marginal fit and anatomical accuracy, addressing critical clinical challenges [7, 9].

Moreover, 3D printing has expanded the scope of zirconia use by overcoming some of the limitations associated with traditional subtractive techniques, such as the difficulty of achieving optimal translucency and surface finish(3,10). Advances in pre-colored zirconia materials and sintering technologies have further improved the esthetic outcomes of 3D-printed restorations, making them suitable for both functional and cosmetic applications(10). Studies have demonstrated that the optical properties of these materials, such as translucency and shade matching, are now comparable to or better than conventionally milled alternatives(10,11).

These developments have driven increased adoption of 3D printing in the fabrication of anterior and posterior restorations.

The clinical implications of these advancements are profound, as 3D-printed zirconia crowns not only meet functional requirements but also enhance patient satisfaction by reducing chairside time and providing more predictable outcomes(1,7,11). Furthermore, the reduced material waste and streamlined production process associated with 3D printing align with the growing emphasis on sustainability in dental practices (1,8). By enabling faster production cycles and offering cost-effective solutions, this technology has the potential to transform the economics of restorative dentistry, making high-quality prosthetics more accessible to both clinicians and patients (11).

While 3D printing offers significant advantages in terms of customization, efficiency, and esthetics, it is not without its limitations. Challenges such as the high initial costs of equipment, the need for specialized training, and material constraints must be addressed before this technology can be widely adopted in all clinical settings(1,6,8). Additionally, concerns about the long-term durability of 3D-printed zirconia restorations, compared to those produced through traditional methods, remain under investigation(7,11). As with any emerging technology, further research and clinical trials are required to fully understand both its benefits and potential drawbacks.

This literature review aims to provide a comprehensive overview of the advancements in 3D- printed zirconia crowns, with an emphasis on physical, mechanical, and aesthetic properties. It will also explore the manufacturing techniques used, the clinical performance of these crowns, patient satisfaction, and the economic implications of adopting this technology (1,11).

DISCUSSION

Physical Properties

Density and Microstructure:

Zirconia is known for its high density and microstructure, which contribute to its superior strength and durability in dental restorations (7,12). Studies have demonstrated that the density and microstructure of 3D-printed zirconia crowns are comparable to, or even better than, those produced through traditional milling methods(9,13). 3D printing techniques, such as stereolithography (SLA) and digital light processing (DLP), allow for precise control over the deposition of zirconia, resulting in uniform density and consistent material properties throughout the restoration(6,8). This consistency is critical in ensuring the long-term durability and functionality of dental crowns(10,14).

Trueness and Precision of Fit:

The trueness and precision of dental restorations are key factors in achieving proper occlusion, minimizing microleakage, and ensuring the longevity of the restoration(7, 13). Studies have shown that 3D-printed zirconia crowns exhibit high trueness and precision of fit, with accuracy levels comparable to those achieved by traditional CAD/CAM-milled crowns(7,12). The ability to customize the design and printing process allows for a better fit that can be tailored to the specific needs of individual patients[9]. This precision in fit is crucial for ensuring patient comfort and reducing the risk of post-operative complications [4,14].

Surface Roughness: Surface roughness is an important factor in both the aesthetic appearance and functionality of dental restorations[9,14]. 3D-printed zirconia crowns are capable of achieving a smoother surface finish than milled crowns, due to the precision of the printing process[9,10]. Surface roughness plays a role in preventing plaque accumulation and maintaining oral hygiene, as smoother surfaces are less likely to harbor bacteria[10,14].

Additionally, smooth surfaces contribute to the aesthetic appeal of the restoration, as they can be polished to achieve a natural tooth-like finish[10, 14].

Mechanical Properties

Fracture Toughness and Flexural Strength:

Fracture toughness and flexural strength are critical properties for the performance of dental crowns under the masticatory forces experienced in the oral cavity[12,14]. Research has indicated that 3D-printed zirconia crowns demonstrate fracture toughness and flexural strength that are comparable to, or even superior to, those of milled zirconia crowns[10,14]. This is primarily due to advancements in 3D printing technologies, which allow for precise control over material deposition and sintering processes, resulting in crowns that are both strong and resistant to fracture[9,14].

Hardness and Wear Resistance:

The hardness of dental crowns is important for their resistance to wear over time, particularly in posterior teeth that endure significant masticatory forces[12,14]. Studies have shown that 3D-printed zirconia crowns exhibit hardness and wear resistance that are on par with, or exceed, those of traditional zirconia crowns produced through milling[12,14]. This durability ensures that the crowns remain functional and aesthetically pleasing over extended periods of use, even in demanding oral environments[10,14].

Aesthetic Properties

Translucency and Color Stability:

Aesthetic considerations are paramount, particularly in anterior restorations where the appearance of the crown must closely match the natural dentition[15]. Zirconia's natural translucency makes it an ideal material for dental crowns, as it can be customized to achieve different levels of translucency and color to match the patient's teeth[10]. Studies have shown that 3D-printed zirconia crowns provide superior aesthetic outcomes compared to milled crowns, with enhanced color stability and translucency[10]. The precise control offered by 3D printing allows for greater customization of the crown's appearance, leading to more natural-looking results [9,14].

Surface Finish and Polishability:

In addition to translucency, the surface finish and polishability of zirconia crowns are essential for both their aesthetic and functional performance[10,14]. A smooth surface finish enhances the crown's visual appeal and reduces bacterial adherence, promoting better oral hygiene[10,16]. Studies have demonstrated that 3D-printed zirconia crowns can achieve a high-quality surface finish that surpasses that of milled crowns, contributing to improved aesthetic outcomes and patient satisfaction [10, 16].

Clinical Performance

Clinical Success Rates:

The clinical performance of 3D-printed zirconia crowns has been the subject of studies, with results indicating high success rates [16]. Clinical trials have demonstrated that 3D-printed zirconia crowns offer comparable, if not superior, performance to milled crowns in terms of fit, strength, and aesthetics [16]. This makes them a viable option for various types of dental restorations, including full-arch prostheses and single-unit crowns [16, 17].

Patient Satisfaction:

Patient satisfaction is a critical measure of the success of dental restorations, and studies have consistently shown that patients are highly satisfied with the appearance, comfort, and durability of 3D-printed zirconia crowns [(16)]. The ability to customize the fit and aesthetics of the crowns to the individual patient's needs enhances comfort and functionality, contributing to high levels of patient satisfaction[(16,17)]. Furthermore, the reduced chairside time and faster turnaround associated with 3D printing technology improve the overall patient experience [(1)].

Manufacturing Processes

Additive Manufacturing Techniques:

3D-printed zirconia crowns can be produced using various additive manufacturing techniques, including stereolithography (SLA), digital light processing (DLP), and selective laser sintering (SLS)[(11)]. Each of these methods offers distinct advantages in terms of precision, speed, and material properties[(6,8)]. SLA and DLP, for example, provide high-resolution printing with excellent surface finishes, making them suitable for detailed dental restorations[(6,11)]. SLS, on the other hand, offers higher strength and durability, making it ideal for load-bearing restorations such as posterior crowns[(8,11)].

Post-Processing:

After the printing process, zirconia crowns undergo sintering and polishing to enhance their physical and mechanical properties[(16)]. Sintering is a critical step that increases the density and strength of the crowns, while polishing improves the surface finish and aesthetic appeal[(16,14)]. Post-processing steps are essential to ensure that the final product meets the high standards required for clinical use[(14,16)].

Biocompatibility

The biocompatibility of materials used in dental restorations is a critical factor in their clinical success. Zirconia is known for its excellent biocompatibility, making it suitable for long-term use in the oral environment [(2)]. The ability of zirconia to interact favorably with surrounding tissues, such as gums and bone, without causing irritation or inflammation, is one of the reasons for its widespread use in dental crowns, bridges, and implants [(18)].

In terms of 3D-printed zirconia, studies have demonstrated that the material maintains its biocompatibility even when produced using additive manufacturing methods [(7)]. The sintering process used in 3D printing enhances the material's surface smoothness, which can further improve tissue response and reduce plaque accumulation[(16)]. Moreover, 3D printing allows for more precise control over the design and surface features of the restoration, potentially leading to better integration with surrounding tissues [(2,18)].

While research is ongoing, current evidence suggests that the biocompatibility of 3D-printed zirconia crowns is comparable to or even better than conventionally milled zirconia, owing to the ability to customize the material's surface and microstructure [(16, 18)].

Limitations and Challenges

Despite the clear advantages of 3D printing in dentistry, there are several limitations and challenges that need to be addressed for more widespread adoption. One of the primary barriers is the high initial investment required for 3D printing equipment and the specialized training needed to operate these systems effectively[(6,19,20)]. Dental practices, especially smaller ones, may find it difficult to justify the upfront costs without a clear understanding of the long-term return on investment[(8)].

In terms of the technical limitations, while 3D printing allows for the creation of highly precise and complex restorations, certain anatomical features, such as deep margin lines or areas near the gum line, can be difficult to capture with current technologies [1,10]. Additionally, 3D printing zirconia with full translucency remains a challenge, especially for aesthetic restorations in the anterior region of the mouth where high levels of translucency are required for a natural appearance [10].

Furthermore, achieving consistent outcomes across different labs and machines can be difficult due to variations in the printing process, materials, and post-processing steps[11]. As 3D printing in dentistry continues to evolve, addressing these challenges through further innovation and standardization will be crucial for improving its reliability and accessibility [6, 19].

Regulatory and Standardization Considerations

As 3D printing becomes more integrated into dental workflows, regulatory oversight and standardization play an increasingly important role in ensuring the safety and effectiveness of 3D-printed dental restorations. In many countries, dental restorations are considered medical devices, which means they are subject to stringent regulatory controls to ensure patient safety [11, 19].

One of the key challenges in regulating 3D-printed dental restorations is ensuring the consistency of materials and processes across different laboratories. Since each lab may use different 3D printing technologies, materials, and software, establishing uniform standards for trueness, precision, and biocompatibility is essential[11]. Regulatory bodies such as the U.S. Food and Drug Administration (FDA) and the European Medicines Agency (EMA) are currently working on frameworks that address these concerns, but the rapid evolution of 3D printing technologies often outpaces the development of regulations [11].

Additionally, there is a need for clear guidelines on the post-processing steps, such as sintering and polishing, which have a direct impact on the final product's performance and biocompatibility. As the adoption of 3D printing in dentistry grows, continued efforts to standardize materials and processes will help ensure that dental professionals can reliably produce safe and high-quality restorations [6, 19].

Comparison with Other Materials

While zirconia is one of the most used materials in 3D-printed dental restorations, other materials such as lithium disilicate and resin-based composites are also frequently used for crowns and bridges [3]. Zirconia stands out due to its superior mechanical properties, including higher fracture toughness and wear resistance compared to resin-based materials, making it particularly suitable for load-bearing restorations like posterior crowns [3,14].

Lithium disilicate, on the other hand, offers higher translucency than zirconia, which makes it more aesthetically appealing for anterior restorations where appearance is the primary concern[2]. However, lithium disilicate is generally less durable than zirconia, and its lower strength makes it more prone to fracture under heavy occlusal forces[3].

In terms of biocompatibility, zirconia remains a top choice, as it has been shown to interact more favorably with surrounding tissues, especially compared to resin-based materials [2,3]. The ongoing development of new materials for 3D printing may eventually combine the strength of zirconia with the aesthetic benefits of materials like lithium disilicate, offering even more versatility for dental restorations[3,6].

Long-Term Clinical Outcomes

While short-term studies on 3D-printed zirconia crowns have shown promising results, long-term data is still limited [16]. Clinical studies that evaluate the performance of these crowns over extended periods, typically 5-10 years, are crucial for assessing their durability, wear resistance, and success rates in real-world applications [16].

Preliminary studies suggest that 3D-printed zirconia crowns exhibit similar or better long-term performance compared to milled crowns, particularly in terms of mechanical strength and wear resistance[16,17]. However, further research is needed to determine how well these restorations hold up under different clinical conditions, such as variations in patient diet, oral hygiene, and occlusal forces [16].

Moreover, the ability to customize the design and fit of 3D-printed crowns based on patient-specific data could lead to improved long-term outcomes by reducing the risk of complications such as microleakage or crown failure [14,16]. As more long-term clinical data becomes available, dental professionals will be better equipped to evaluate the overall success of 3D- printed zirconia crowns compared to traditional methods [16].

Environmental Impact and Sustainability

One of the key advantages of 3D printing technology is its potential to reduce material waste and promote more sustainable practices in dentistry [11,20]. Traditional subtractive manufacturing methods, such as milling, often result in significant material loss, as large portions of zirconia blocks are cut away to create the final restoration [6]. In contrast, 3D printing is an additive process, meaning that material is deposited layer by layer only where needed, resulting in minimal waste [8,20].

In addition to reducing material waste, 3D printing can also lower energy consumption by streamlining the production process. For example, traditional manufacturing methods often require multiple steps, including casting, milling, and polishing, each of which consumes energy and resources [11]. By contrast, 3D printing consolidates many of these steps into a single process, reducing both energy use and production time [11].

As dental practices increasingly seek to adopt more environmentally friendly approaches, the sustainability benefits of 3D printing are becoming an important consideration. Furthermore, as 3D printing technologies continue to evolve, there is potential for further reducing the environmental impact by developing recyclable or biodegradable materials for dental applications [19].

Future Technological Trends

Looking ahead, several technological trends are expected to further enhance the capabilities and applications of 3D printing in dentistry. One promising area of development is **hybrid manufacturing**, which combines 3D printing with traditional milling techniques. This approach leverages the strengths of both technologies, enabling dental professionals to create restorations that benefit from the precision of milling and the flexibility of 3D printing [11, 19].

Another exciting trend is the integration of **artificial intelligence (AI)** in dental design. AI-driven software can help optimize the design of dental restorations by analyzing patient-specific data and predicting how the restoration will perform under different conditions [19]. This could lead to more personalized and precise dental treatments, improving both patient outcomes and the efficiency of the design process.

Material innovations are also expected to play a significant role in the future of 3D printing. Researchers are developing new materials that combine the mechanical strength of zirconia with the aesthetic properties of more translucent materials like lithium disilicate, providing greater versatility for different types of restorations [1,6]. As these materials become commercially available, they could greatly expand the clinical applications of 3D printing in dentistry [11].

Cost Implications Cost-Effectiveness:

The cost-effectiveness of 3D-printed zirconia crowns compared to traditional milling methods is a significant consideration for dental practices[8]. While the initial investment in 3D printing equipment can be high, the long-term benefits, including reduced material waste and labor costs, can make 3D printing a cost-effective solution for producing dental restorations [6,8,20].

Furthermore, the ability to produce crowns on-demand reduces the need for large inventories of pre-manufactured crowns, contributing to lower overall costs (1).

Economic Impact:

The broader economic implications of adopting 3D printing technology in dentistry include the potential to reduce healthcare costs and improve access to high-quality dental care (1). By streamlining the production process and reducing turnaround times, 3D printing can make advanced dental treatments more affordable and accessible to a larger patient population [19]. Additionally, the reduced material waste associated with additive manufacturing contributes to the sustainability of dental practices [11].

CONCLUSION

The integration of 3D printing technology in the fabrication of zirconia crowns has demonstrated significant potential for improving dental restoration outcomes. 3D-printed zirconia crowns offer comparable, if not superior, physical, mechanical, and aesthetic properties to those produced by traditional milling methods. The ability to customize the design, enhance precision, and reduce material waste makes 3D printing an attractive option for dental professionals. As technology continues to evolve, it is likely that 3D-printed zirconia crowns will become increasingly prevalent in clinical practice, offering precise, strong, and aesthetically pleasing solutions for patients.

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