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Evaluation of the optical behavior of dental zirconia produced by CAD/CAM milling and 3D printing

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Abstract

Zirconia is widely used in dentistry due to its exceptional aesthetic qualities, high mechanical performance and biological stability. Ceramic additive manufacturing (AM) has received significant attention recently due to its potential to create advanced configurations and structures suitable for certain medical applications, particularly customized devices. Because of its efficiency and freedom, AM zirconia opens up countless possibilities that would be almost impossible with traditional methods. The review examined the accuracy, biocompatibility, physical and adhesive properties, and clinical applications of AM zirconia. Here we highlight the optical behavior characteristics of 3D printed zirconia. This review followed the PRISMA-ScR guidelines. Electronic searches were conducted in PubMed, Scopus, Web of Science, and Embase for studies published between 2015 and 2024 using the keywords 'zirconia', '3D printing', 'CAD/CAM milling', and 'optical behavior'. Articles focusing on translucency, gloss, scattering, and reflectance of dental zirconia were included. In summary, this review provides a new and essential general basis for the application of 3D printed zirconia in dentistry as well as a descriptive account of the basic optical behavior properties of AM zirconia materials for oral medicine.

Keywords:optical behavior, zirconia, CAD/CAM milling, 3D printing

Introduction

Due to the complex optical properties of teeth, achieving a natural appearance with an artificial restoration is a challenging process [1]. Over the years, metal-ceramic restorations have been considered the gold standard in dentistry due to their increased strength and long-term durability [2]. The optical phenomena with properties such as transparency, opacity, fluorescence, opalescence and metamerism play an essential role in the concept of color in dentistry. Understanding these phenomena is critical to achieving natural-looking restorations that mimic the optical properties of natural teeth [3]. Dental materials that can reproduce these optical properties enable more realistic and aesthetically pleasing restorations. With the right materials, high quality results can be achieved that exceed normal expectations [4].

Optical materials change the direction and phase of light through refraction, reflection, transmission, etc. under the influence of external fields (light, electric and magnetic fields, sound, temperature, pressure, etc.), so that light can be transmitted or absorbed according to predetermined requirements transmitted over a certain wavelength range, changing the intensity and spectrum of light to achieve the purpose of detection, modulation and energy conversion [5]. Optical materials include polymers, metals, ceramics and nanocomposites [6]. The polymers are primarily used for optical applications such as windows and lenses because they have a wide range of transparency with a refractive index between 1.3 and 1.75. Polymer optics can be manufactured from materials such as polycarbonate, styrene, CR-39 or Zeonex E48R through stamping, die casting or injection molding processes [6]. Although these methods are suitable for mass production, it is relatively difficult to accurately control the temperature, injection pressure and injection speed during the manufacturing process [7]. In the field of ceramics, glassy quartz glass (SiO_2), soda-lime silicate glass, sodium borosilicate glass and lead oxide glass are often used to produce optical devices such as telescopes, microscopes and binoculars [8].

The production of glass must be carefully and strictly regulated to ensure its purity and the predetermined parameters to meet the desired properties, since the raw glass has low reflectance and high emissivity [8,9]. Nanocomposites with improved mechanical and electrical properties have been successfully fabricated in bioinspired structures [9–14]. ZrO_2 nanoparticles [14], ZnO nanoparticles [15], organic-inorganic sol-gel composites [16] and other nanocomposites can be integrated. The optical properties of optical devices such as absorption, fluorescence and broad refractive index can be significantly improved by incorporating them into polymer or ceramic matrix materials [17]. For actual production, more nanocomposites with superior optical performance need to be researched and developed

Zirconia-based restorations have been widely used in dentistry for the past 20 years. To achieve good esthetic results, patients often choose metal-free restorations, using materials with the same quality as natural teeth and similar properties such as light scattering] .[18Zirconia is a remarkable example of a polycrystalline ceramic that lacks glass components and has a thick, cohesive structure that makes it exceptionally difficult to fracture [19].

Over the last 20 years, zirconia-based restorations have become increasingly popular in dentistry. To achieve good aesthetic results, patients often choose metal-free restorations with comparable quality to natural teeth and comparable properties such as light scattering [18]. An outstanding example of a polycrystalline ceramic without glass components is zirconium oxide, which has a thick, coherent structure that makes it very difficult to break [19,20]. In addition, it has low thermal conductivity, polishability, hardness, minimal thermal conductivity, high biocompatibility and chemical stability [21, 22]. In addition, it is well suited for replacing single and multiple teeth in the anterior and posterior areas. It also exhibits unique crystallographic structures such as cubic, tetragonal and monoclinic structures, which contribute to its variety of mechanical and optical properties [23].

Over the last decade, the dental field has introduced CAD/CAM technologies that have reduced human error in restoration fabrication and model creation. These digital systems are constantly evolving and getting better. Although additive techniques such as printing have only recently been introduced, computer-aided manufacturing has historically been carried out through subtractive processes such as milling [24]. Reduction techniques use computer-controlled machines with multi-axis milling systems to mill the prosthesis from a high-quality industrial blank, either a block or a disc. The degree of freedom of the cutter and material movement limits complex geometry, cutting tool size and speed, which determine the minimum feature size and surface finish. To create a finished prosthesis, additive methods are used to apply successive layers of liquid or powdered materials, layered vertically and fused using 3D model data. To stabilize or support the part during the layering process, these techniques also utilize additional support structures [25].

Vat photopolymerization (stereolithography [SLA], digital light processing [DLP]), direct injection printing, fused deposition modeling (FDM), selective laser sintering (SLS) and selective laser melting (SLM) technologies, robocasting, direct energy deposition, sheet metal lamination and binder jetting are some of the Printing technologies that have been used for 3D printing of ceramics [26–28]. Both printing and milling techniques have advantages and disadvantages [29].

The use of CAD/CAM milling has several advantages, including the ability to predict material properties, resulting in denser structures, precision and accuracy in shape reproduction, significant time and labor savings, and the possibility of using any material [30]. The waste of a large amount of raw materials (materials for supports and milled disc scraps that cannot be reused) is one of the limitations of milling. Drills are subject to abrasive wear during milling, especially when grinding blocks of fully sintered ceramic material [31]. Although these blocks are dimensionally stable, grinding can produce tiny cracks in the ceramic surface, which could shorten the lifespan of the restoration [31, 32]. Pre-baked blocks or slices offer a legitimate substitute. By using these materials more efficiently, the drill bits are not damaged. However, after curing, dimensional changes of the restorations may occur, which could somewhat affect the accuracy [31]. As a result, in some applications the drill has difficulty reaching smaller cavities and/or avoiding undercuts (e.g. when milling zirconia abutments) [31]. Other disadvantages include the size of the milling head and the axis' limited ability to produce complex shapes, which increases maintenance and equipment costs and makes it difficult to locate in an office.

These problems should be solved by modern methods of additive manufacturing (AM) or 3D printing [33, 34]. Nowadays, prosthodontists around the world use AM to produce resin components (e.g., prosthetic abutments, temporary restorations) and metal [35–37]. To create complicated structures, 3D printing gradually hardens liquid resin using light or lasers. 3D printing can be done using a laser stereolithography (SLA) machine, which uses a laser beam to cure the liquid resin in incremental lines, or fused deposition modeling (FDM), which uses a solid resin filament that passed through a nozzle is ejected as fine lines [38-40]. Because SLA printers can produce structures with a resolution of just 25 micrometers, they are more commonly used than FDM printers, which can only produce structures with a resolution of around 100 micrometers. Compared to milling technologies, 3D printed resin structures can use up to 40% less material [41, 42]. In order to obtain the finished product, structures printed using the SLA process must be post-processed [43].

3D printers come in a variety of models, from inexpensive home models to more expensive laboratory models. Without the limitations associated with the use of additional tools for traditional molding, casting and milling processes, 3D printing enables the production of extremely complex objects [41–43]. Other benefits of 3D printing include the possibility of having a printer in the office, avoiding material waste, and potentially reducing working hours [43]. Thanks to recent technological advances, zirconia can now be 3D printed [44–46]. The interfaces between printed layers can be weak points, dense structures are difficult to create, the range of materials that can be treated with light or laser is limited, and printing large, complicated structures can be time-consuming. Nevertheless, the topic of 3D printed prosthetic restorations made of zirconium oxide has received little attention so far [18]. There are no significant studies examining the optical performance of 3D printing and CAD/CAM milling of zirconia, and because 3D printing of ceramic dental restorations is still in its infancy, little is known about the color behavior and optical properties of 3D -printed all-ceramic restorations [47, 48]. Therefore, the aim of this review is to compare the optical behavior of dental zirconia made by CAD/CAM Milling and 3D printing.

Search Strategy and Methodology

This review was conducted in accordance with the PRISMA-ScR (Preferred Reporting Items for Systematic Reviews and Meta-Analyses for Scoping Reviews) framework. A systematic search was performed in PubMed, Scopus, Web of Science, and Embase databases for articles published from 2015 to 2024. The search terms included combinations of 'zirconia', 'optical behavior', 'translucency', 'CAD/CAM milling', and '3D printing'. Inclusion criteria comprised original in vitro or in vivo studies, reviews, and experimental reports evaluating optical characteristics such as translucency, gloss, reflectance, and scattering of dental zirconia. Exclusion criteria included non-dental applications and non-English papers. Two reviewers independently screened titles and abstracts, followed by full-text analysis. Relevant data were extracted and summarized descriptively.

Optical behavior features

Optics is an important branch of science that studies the generation, propagation, and display of electromagnetic radiation in a wide range of wavelengths ranging from terahertz wave, infrared, and visible light, to ultraviolet, as well as the interaction with matter [49,50]. The instruments that produce, manipulate, and detect light are optical elements. Kubelka-Munk scattering coefficient (S), absorption coefficient (K), transmittance (T%), reflectance at infinite thickness (RI) and infinite optical thickness (X∞) are important properties in the investigation of optical behavior[.[52 ,51] Since these optical parameters are wavelength-dependent, their values vary across the visible spectrum. Also, the albedo coefficient will be used to assess how absorption and scattering processes contribute to the quenching of light when passing through an analyzed 3D printed sample. Provisional restorations should have optical properties very similar to final restorations. This allows the doctor and patient to visualize the aesthetics of the final restorations before they are fabricated. The translucency of this acrylic material gives a temporary restoration a life-like appearance. To achieve the best esthetics, a restorative material must interact with light in the same way as a natural tooth. Another important property is gloss, which measures the reflectance of a surface. Gloss unit (GU) values range from 0 to 100 with less than 10 GU indicating low gloss and 70 GU or higher considered high gloss [53-56].

Clinical characteristics for restorations with translucent zirconia

One of the main elements affecting aesthetics is translucency, which is a crucial characteristic when selecting ceramic materials [57,58]. One of the main materials of the frameworks, which are additionally layered with translucent porcelain, is zirconium oxide due to its opacity. The zirconium core is whiter than the core of metal-ceramic restorations; The ceramic layer can be more translucent, allowing the zircon core to show through. However, the high chipping rate is a common problem with ceramics applied over a coping layer. The introduction of monolithic zirconia restorations reduced the risk of ceramic chipping and fracture. Compared to metal-ceramic restorations, monolithic zirconium oxide restorations are said to require less tooth structure reduction. Chips and fractures are less likely due to the flexural strength and fracture toughness of monolithic zirconia. Nevertheless, posterior bridges with more than three units made of cubic zirconium oxide are not recommended [59, 60].

Since pores compact and shrink independently of the matrix due to light scattering and agglomerations after heat treatment, the microstructure of the materials is the main influencing factor for their optical properties. This causes large grains to form in the materials, which also lead to the formation of intergranular and intragranular pores as well as the removal of intragranular pores [61]. Researchers have studied zirconia materials created using 3D printing and two-photon lithography. They emphasized that the formation of microceramics in the pure and stable cubic phase was enabled by zirconia nuclei and that shrinkage due to loss of organic matter was significantly reduced compared to the acrylate system. Furthermore, the addition of nanoparticles significantly improves the optical properties of the microfabricated structures even when no heat treatment is performed [62,63].

Effect of zirconia printing method on optical behavior

Manufacturing methods have a significant impact on the optical properties of zirconium oxide based systems. Dental technicians and dentists should have sufficient knowledge to determine the best manufacturing methods and materials for the best optical and aesthetic results. This means that better aesthetics can be achieved by choosing more suitable restorative materials [64].

Savaş et al., (2021) investigated how five different fabrication methods influenced the optical properties of zirconia-based systems, including color differences between the different shades (ΔE*ab, ΔE00), transparency, opalescence and fluorescence (ΔE*ab-FL). They found that the manufacturing methods had a significant impact on the optical properties of the zirconia-based systems, even if they had the same nominal hue. was employed; Therefore, for appropriate color matching, the transparency, materiality, fluorescence and color rendering of the materials should be taken into account [65].

Since ceramics with low opalescence cannot reproduce the vital appearance of a natural tooth, opalescence is important for aesthetics. If the OP value is below 4, opalescence is absent. If the OP value is between 4 and 9, some opalescence can be observed, but it is hardly noticeable to the naked eye [66]. Small amounts of inorganic oxides, including yttrium, cerium, bismuth, europium and titanium oxides, are incorporated into the ceramic to create a fluorescent substance known as luminary, which lightens color without affecting the translucency of dark teeth [67, 68].

Effect of zirconia polishing on optical behavior

Grinding, polishing, and glazing are vital steps in clinical treatment, aimed at improving the optical and aesthetic characteristics of zirconia. By effectively treating additive-manufactured zirconia to enhance its density, its applicability in clinical settings is significantly improved [69,70]. A study conducted by Mitov et al., (2012) revealed that the rough surfaces of monolithic zirconia restorations can contribute to greater wear on the enamel of antagonistic teeth, indicating that polished monolithic crowns are less abrasive [71]. Stawarczyk et al., (2013) found in their study that glazed monolithic translucent zirconia restoration presents the most abrasive ceramic surface for antagonist enamel, while the polished zirconia is the least abrasive [72]. Mundhe et al have shown that polished zirconia restorations cause less tooth structure wear of the opposing enamel than feldspathic ceramics [73]. Janyavula et al., (2013) compared in their study the roughness of polished, glazed, polished, and glazed veneered monolithic zirconia restorations [74]. Their findings revealed that polished zirconia has the smoothest ceramic surface. However, additional studies indicated that polished translucent zirconia restorations also feature a very smooth surface. Consequently, the ceramic surfaces of these dental materials are less abrasive when compared to other ceramic systems, including lithium disilicate [75]. In specific clinical situations, monolithic restorations created through CAD/CAM milling may have basic contours that lack a natural texture. To obtain a more natural appearance, dental technicians can implement texturizing techniques according to a defined protocol. McLaren's research indicated that simply glazing translucent zirconia does not achieve a natural look for the restoration [76]. Rinke et al., (2013) recommended that polishing techniques provide a more authentic and realistic appearance than glazing. Nonetheless, in certain clinical scenarios, surface staining pigments can be applied to create a more personalized characterization [70].

Lu et al., (2024) stated that the milled and both 3D-printed groups showed similar phase compositions for the as sintered condition. Considerable amounts of rhombohedral phase were detected after polishing. Milled unpolished samples presented significantly higher fatigue strength than 3D-printed unpolished samples. Polishing did not improve the fatigue strength for milled zirconia but was advantageous for the 3D-printed specimens. 3D-printed specimens with parallel printing-layer orientation were significantly stronger than specimens with perpendicular layers regardless of surface finishing. The manufacturing techniques had a significant influence on the fatigue strength of 3Y-TZP, but not on the phase compositions of the surface. The polishing protocol showed different effects on 3Y-TZP fatigue strength and induced phase transition of the 3Y-TZP from Tetragonal to Rhombohedral. The best fatigue strength was achieved through milling using an unpolished surface and SLA-printed layers that were parallel to the tensile surface, followed by polishing [77].

Effect of thickness on optical behavior in 3D printing

The mechanical and optical properties of monolithic restorations are influenced by the material thickness [78]. Kanchanavasita et al., (2014) found that translucency is significantly influenced by material thickness and that translucency increases with decreasing thickness [79]. For all-ceramic restorations, a thickness of 1–1.5 mm is typically required [80]. In Özel et al., (2023) In order to correspond to the crown thicknesses used in the clinic, the samples study were prepared with a thickness of 1 to 2 mm [81]. Surface finishing techniques are well suited to the translucency and thickness of ceramics [82]. Reportedly, the glaze layer in glazed monolithic zirconia gradually wears away, causing the restoration to wear away the adjacent tooth or the restoration [83]. For this reason, polishing is considered a better surface finishing method for zirconia restorations than glazing [84]. Likewise, polishing of the ZLS and LS2 restoration surfaces has been reported to be sufficient for both wear and plaque retention [85].

Sasany et al., (2024) stated that scattering coefficients (S) (79% ≤ VAF ≤ 100%) and absorption (K) (40.45% ≤ VAF ≤ 100%) spectral distribution depended on the wavelength. A 25-µm layer thickness resulted in no significant differences from the 2M2 shade for S (P > .230) and K (P > .200). VS showed significantly different S (P = .004) and K (P = .003) values from those of the shade tab with 50-µm layering thickness, whereas other materials did not show significant differences from the 2M2 shade for S (P > .280) and K (P > .301). The 100-µm layer thickness specimens had significantly different S and K values compared to the 2M2 shade tab (P < .004). TP values of resins with 100-µm layer thickness were significantly lower than resins in 25- and 50-µm layer thicknesses (P < .001). The Ra values of resins increased significantly with 100-µm layer thickness (P ≤ .001). also, They stated that all tested materials, except for VS, showed color properties similar to the target shade when 25- and 50-µm printing layer thicknesses were used. The translucency of resins tended toward an inverse relationship with printing layer thickness. The surface roughness of resins increased significantly with 100-µm layer thickness.

Sasany et al., (2024) indicated that wavelength affects the spectral distribution of scattering coefficients (S) (79 percent ≤ VAF ≤ 100 percent) and absorption (K) (40 points 45 percent ≤ VAF ≤ 100 percent). For S (P > .230) and K (P > .200) there were no significant deviations from the 2M2 shade at a layer thickness of 25 µm. While other materials showed no significant differences from the 2M2 shade in S (P > 0.280) and K (P > 0.301), VS showed significantly different S (P = 0.004) and K (P = 0.003) values. those of the color tab with a layer thickness of 50 µm. The S and K values of the samples with a layer thickness of 100 µm were significantly different from those of the 2M2 color palette (P <0.004). Resins with a layer thickness of 100 µm had significantly lower TP values than those with layer thicknesses of 25 and 50 µm (P < 0.001). At a layer thickness of 100 µm, the Ra values of the resins increased dramatically (P ≤ .001). Furthermore, they claimed that when using print layer thicknesses of 25 and 50 µm, all tested materials - with the exception of VS - had color properties comparable to the target shade. The thickness of the print layer tended to be inversely correlated with the light transmittance of the resins. At a layer thickness of 100 µm, the surface roughness of the resins increased significantly. Nevertheless, all resins showed superior color and surface roughness when printed at 25 µm thickness. According to these results, the optical properties and surface roughness of resins were significantly affected by the thickness of the printing layer and the material type [86].

Espinar et al., (2023) showed that as thickness of the 3D-printed resins increased, the absorption and scattering increased, and transmittance and infinite optical thickness decreased. These findings are in accordance with previous studies using dental resin-based composites [87]. Using two-flow KM reflection theory, they investigated how thickness and pressure orientation affect the spectral optical behavior of these biomaterials [87]. Their results showed clear differences in the optical property values of the examined thicknesses for both printing orientations and all materials used. The thickness at which a translucent material reaches 99.9 percent of its light reflectivity and becomes almost opaque when placed against a black background is called the infinite optical thickness ($X\infty$) [88]. The resin can show its natural color without being affected by the background color when the thickness of the restoration is greater than the infinite optical thickness. Therefore, to eliminate the effect of background color, the material thickness should be greater than the infinite optical thickness of the same material. In the event that such thickness is not possible, the influence of background color on maskability should be reduced or eliminated by using primers [87]. Overall, the T percent and S-K coefficient values of the 3D printed resins showed comparable spectral behavior. Since these materials primarily scatter and absorb visible light at short and medium wavelengths, long wavelengths have the highest transmittance. Particle size is the main factor affecting the scattering coefficient of a resin-based composite, and S reached its maximum when the particle diameter was equal to or larger than the incident wavelength. Particle size is the most important factor affecting the scattering coefficient of a resin-based composite, with S reaching its maximum when the particle diameter equals or exceeds the wavelength of the incident light [89,90]. In contrast, absorption depends on the resin matrix and the type of color pigments [91]. Compared to DFT, FT and FP materials, GCT showed significantly greater spectral dispersion and absorption as well as lower transmittance for each thickness evaluated. Since DFT contains only 0–8% silica filler while GCT contains 20 wt% homogeneously dispersed silane-coated silica fillers and antisedimentation fillers, this behavior could be due to differences in chemical composition. The increased scattering in this material may be due to the higher filler content [87].

Effect of Printing features on optical behavior of Zirconia ceramics

Many researchers have paid great attention to the zirconia sintering process, which is considered an essential step in the production of ceramics [92,93]. Previous research has shown that variations in the sintering process have a direct impact on density. including particle size and phase composition, which significantly influence the optical and mechanical properties of zirconia [94]. For Y-TZP ceramics, the conventional sintering program is often expensive and time-consuming [95]. Therefore, rapid sintering has been proposed as a potential method to shorten processing time and maintain high material density while inhibiting particle growth through rapid heating, ultimately leading to a refined microstructure [96]. Numerous studies have been conducted to investigate how different sintering conditions affect the strength, microstructure, and optical properties of zirconia core ceramics. Ersoy et al., (2015) showed that the combination of a high sintering temperature with a short sintering time increased the flexural strength of zirconium oxide [97]. Liu et al., (2022) showed that the flexural strength is not significantly influenced by changing the sintering program [98]. However, the influence of changed sintering conditions on the strength and translucency of monolithic zirconia is still under debate [99–102].

Espinar et al., (2023) evaluated the influence of printing orientation on color and translucency of 3D printing restorative resins. They indicated that In general, color changes due to printing orientation at (0° and 90°) were mainly produced by ΔL* or ΔC* . ΔE00 were above PT00 for all DFT shades, FP-B1, FP-C2, FT-A2 and FT-B1. Only for DFT-1, ΔE00 was above AT00. ΔRTP00 values were above TPT00 for DFT-A1, DFT-A3, FP-B1 and FT-B1, but lower than TAT00. The direction of the changes in translucency (ΔRTP00) depends on the material and shade. This study showed that the selection of building orientation (0° and 90°) for the 3D printed resins influences the visual color and translucency and therefore their esthetic appearance. These aspects should be considered when printing dental restorations using the evaluated materials [103].

· Effect of Printing speed on optical behavior of Zirconia ceramics

Speed sintering was introduced to fabricate time-efficient chairside restorations, however, its influence on the microstructure and optical properties of zirconia is still unclear [95]. Cho et al., (2023) aimed to investigate the effect of high-speed sintering on the translucency and opalescence parameters (TP and OP, respectively), as well as their related microstructure and phase distribution, using two types of multi-layered 5Y-zirconia. They stated that regardless of the zirconia type, the TP was slightly lowered by high -speed sintering in all the layers except the dentin layer (DL) for Lava Esthetic ($p < 0.05$). The OP decreased by high-speed sintering in the DL for Cercon xt ML and in all the layers for Lava Esthetic ($p < 0.05$). The decrease in translucency after high-speed sintering was attributed to a decrease in the yttria-rich t'-phase with low tetragonality, along with an increase in the yttria-lean t-phase with high tetragonality [104]. Abed et al., (2024) determined the impact of the speed sintering program on the microstructure, flexural strength and translucency of zirconia in comparison with those of the conventional sintering program. they showed that the grain size, flexural strength, and translucency results showed increasing trends when speed sintering was compared with the conventional one but the differences were not significant ($P > 0.05$) [105]. Shohdy et al., (2024) Speed sintering significantly reduced the translucency and opalescence compared to conventional sintering excluding the opalescence of the dentin layer. Chromaticity significantly decreased with speed sintering in less chromatic layers and significantly increased in more chromatic layers. Mean color change ranged between 0.65 and 1.25 across different layers. Mean crystal size decreased with speed sintering [106]. Mohamed et al., (2024) stated that Speed sintering statistically changed both the optical (CR, TP, Tt%) and mechanical (flexural strength) properties of multi-layered zirconia materials, but the differences may not be clinically relevant [107].

· Effect of Printing layer thickness on optical behavior of Zirconia ceramics

Layer thickness, laser intensity, laser speed, construction angle, support structure geometry, and printing technology all have an impact on the efficiency of 3D printing [108–110]. The accuracy of the final restoration, which is determined by correctness and precision [111], is influenced by the controllable parameter of layer thickness [112]. Therefore, determining the ideal layer thickness is crucial to achieve the best results. Furthermore, layer thickness has been shown to influence both printing accuracy and printing speed [113]. The layer thickness of a photopolymerization-based 3D printer is typically between 20 and 150 μm [112]. Previous studies on 3D printed interim materials mainly examined the influence of printing orientation [108,114,115], while the effect of layer thickness was mainly evaluated by printing individual trays [117], trial dentures [116] and tooth models [113]. The influence of layer thickness and pressure orientation on the fit of three-unit implant-supported fixed partial dentures has only been investigated in one study [118, 119].

Clinical Implications

Clinically, both CAD/CAM-milled and 3D-printed zirconia restorations can achieve acceptable esthetic outcomes. However, clinicians must consider that printed zirconia is more sensitive to parameters such as printing angle, layer thickness, and sintering conditions. Proper surface polishing enhances gloss and reduces antagonist enamel wear. Given the increasing clinical interest in additive manufacturing, optimizing post-processing and sintering protocols is essential to match or exceed the performance of milled zirconia.

Conclusion

3D printing introduces significant flexibility in the design and fabrication of dental zirconia restorations while maintaining satisfactory optical properties. Milled zirconia continues to offer superior mechanical strength and homogeneity. Optical properties of 3D-printed dental resins can be mainly evaluated by the scattering (S) and absorption (K) coefficients, light reflectivity (RI) and infinite optical thickness , and these parameters can be determined using two-flux Kubelka-Munk's (K-M) equations. Future studies should focus on standardizing optical testing methods, improving printing resolution, and investigating the influence of aging, thermocycling, and long-term color stability. Moreover, hybrid manufacturing strategies that combine additive and subtractive processes may offer enhanced outcomes in both esthetics and functionality.

Author Contributions

All authors associated with the conception and design of the investigation, who had the article correction [**Elham Moghadas**], who carried out the study data analysis and literature review, [**Roya Piryaei**], [**Zahra Bahadori Monfared**], [**Fatemeh Alipour Yalda**], [**Hoda Mosadegh Khah**], and who drafted review [**Roya Piryaei**], and revised critically the full original study [**Elham Moghadas**] and [**Roya Piryaei**]. All study colleagues were free to comment on earlier versions of the manuscript, as well as to read and approve the final manuscript. Finally, [**Elham Moghadas**] who is responsible for the originality of our work and supervised me in this article.

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Declaration of the Conflict Interest

Hereby, we declare that are not any kind of conflict of interests.

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