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REVIEW ARTICLE

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The influence of altering sintering protocols on the optical and mechanical properties of zirconia: A review

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Abstract

Objective: As a result of advancements in chairside technology and speed sintering techniques and increased esthetic demands of patients, efforts have been made to produce monolithic zirconia restorations that are highly translucent, strong, and dense. While methods for processing zirconia are well known, there is a tendency to modify the process parameters with the aim of decreasing the overall processing time and, in particular, the sintering time. This review provides clinicians with scientific evidence of the effects of altering sintering parameters used for dental zirconia on its microstructure, phase transformation, and mechanical and optical properties.

Materials and Methods: A systematic search of Embase and Medline using Boolean operators was performed to locate relevant articles.

Results: Eleven articles were selected for this review. The following characteristics of monolithic zirconia have been confirmed to be affected by alterations in sintering: the microstructure, mechanical properties, optical properties, wear behavior, and low thermal degradation.

Conclusions: The alteration of sintering parameters has been found to alter the grain size, wear behavior, and translucency of zirconia. There is a lack of clinical studies that investigate the influence of altering sintering parameters or methods on the clinical performance of monolithic zirconia restorations.

Clinical Significance: Alteration of sintering parameters alters the microstructural, mechanical, and optical properties of zirconia. This will consequently impact the clinical performance of zirconia prostheses. Future clinical investigations are encouraged to support these in vitro findings.

KEYWORDS
esthetics, microstructure, sintering, translucency, zirconium oxide

1 | INTRODUCTION

The significant clinical acceptance of zirconia for use in indirect dental prostheses has led to numerous dental material companies selling zirconia because of the simplicity of its fabrication, white color, and improved mechanical properties. Zirconia has been increasingly used for multiple dental applications, such as the fabrication of all-ceramic copings, fixed partial prostheses,[1,2] and full-arch dental prostheses,[3] as well as implant abutments and implants.[4] Clinical studies have shown that zirconia-based prostheses may serve as viable long-term restorations.[2,5-8] However, technical problems associated with the clinical performance of zirconia crowns and fixed dental prostheses have been reported, in particular, chipping of the veneering porcelain when applied to zirconia framework structures and loss of retention.[2,5-7] Attempts to minimize the chipping of veneering porcelain by milling the veneers and frameworks separately and subsequently luting them with either luting agent or using fusing firing (CAD on) has not been quite sufficient to address the chipping concerns.[9] Another attempt to overcome the veneer chipping problem was the introduction of zirconia in the form of fully anatomical contoured monolithic prostheses intended to be used without veneering porcelain.

Zirconia is a polymorphic material that exists in three allotropes; the monoclinic phase (*m*) is stable at room temperature and at temperatures up to 1170°C, at which point it converts to the tetragonal phase (*t*), which is stable up to 2370°C, after which it transforms to the cubic phase (*c*), at which it remains until it reaches its melting point of 2680°C.[1,2] This two-way, temperature-driven phase transformation leads to changes in the zirconia molar volume, which is damaging in pure zirconia but can lead to greater strength in the tetragonal and cubic phases if it is stabilized by admixtures, for example, yttrium oxide. Zirconia's high fracture toughness significantly extends the reliability and lifetime of stabilized zirconia products.[10] Furthermore, zirconia ceramics have been reported to not have toxic or genotoxic effects and to present satisfactory tissue responses.[11] In addition, zirconia is a thermal and electrical insulator, and it has a high melting temperature (2680°C).

The main drawback of zirconia is “low thermal degradation” (LTD), which is defined as the spontaneous $t \rightarrow m$ transformation that occurs over time at low temperatures (eg, 37°C) and in the presence of fluids when transformation is not triggered by the local stress produced at the tip of an advancing crack.[12] Although LTD has been investigated and identified as the major cause of failure of zirconia implants (femur head replacements) in orthopedics, it has been poorly investigated and is largely ignored as a potential problem for zirconia in dental applications.[13-15] In the current literature, despite the potential long-term problems derived from LTD, 3 mol% yttria-stabilized tetragonal zirconia polycrystalline ceramic (3Y-TZP), which is considered to be the first generation of zirconia, has been shown to have excellent strength and fracture toughness based on short-term laboratory testing.[11] Many factors can affect LTD, including the stabilizer type and content, residual stress and grain size. The extrapolation of the LTD rate and the estimation of the expected lifetime of zirconia restorations by accelerating aging can lead to unacceptable conclusions that may affect clinical performance,[16] for example, increases in surface roughness and monoclinic contents, with concomitant decreases in hardness and modulus of elasticity. Several solutions have been proposed to minimize LTD with the use of 3Y-TZP, including adding a small amount of silica,[17] using a yttria coating rather than coprecipitated powder, reducing the particle size[18] and increasing the stabilizer content or the formation of composites with Al_2O_3 codoping of Ce nitrate using liquid infiltration.[10]

Zirconia is an opaque monochromic material. Therefore, two principal techniques have been developed for coloring zirconia restorations to overcome esthetic problems and to decrease zirconia opacity. One technique involves the use of “precolored zirconia,” which is based on adding metal oxides to the Y-TZP powder before pressing the milling blocks and then sintering them at high temperature.[19] The other technique involves the immersion of milled zirconia restorations in coloring liquids, such as chloride solutions (rare earth elements), before sintering to achieve the desired shade.[19]

Various types of zirconia are available for use in dental applications. (i) The *first generation*, *tetragonal zirconia polycrystals (3Y-TZP)*, consists of 5.2 wt% or 3 mol% Y_2O_3 dopants and 0.25 wt% Al_2O_3 and has a small grain size (0.3-0.5 μm), high fracture toughness (9-10 MPa/m^2), high flexural strength (900-1200 MPa), and a Young's modulus of 210 GPa at room temperature.[20] It is relatively sintered at a low temperature. Recently, advanced protocols have been developed to reduce the opacity of zirconia and make it more translucent by intensifying the heat treatment conditions.[20] (ii) The *second generation*, *partially stabilized zirconia (3Y-PSZ)*, is doped with 3 mol% of Y_2O_3, but the sintering aid (0.25 wt% Al_2O_3) is eliminated, and the sintering temperature and/or duration is increased. The grain size of 3Y-PSZ is increased to 0.5 to 0.7 μm, and the cubic phase content is increased from 6-12% to 20-30%. As a consequence, the translucency is increased to TP = 24 to 31, and the biaxial strength is decreased to 900 to 1150 MPa.[20] An additional approach that can be used is to replace tetragonal zirconia grains with optically isotropic cubic zirconia particles by increasing the yttria content to diminish the grain boundary light scattering to yield fully stabilized zirconia.[21] (iii) The *third generation*, *4-5Y-PSZ*, incorporates more optically isotropic cubic zirconia (50-80%), has a grain size of 1 to 4 μm and is produced by increasing the Y_2O_3 dopants to 4 to 5 mol% and increasing the sintering temperature and/or duration more than that of the second generation. However, cubic zirconia is weaker and more brittle than its tetragonal counterpart, which jeopardizes the strength of the zirconia. The translucency is increased to TP = 30 to 43, and the biaxial strength is decreased to 450 to 740 MPa. Other types of zirconia include zirconia-toughened ceramics and alumina-toughened zirconia.[1] Additional experimental novel zirconia types with improved translucency have been developed, including graded zirconia and nanostructured zirconia.[20]

In contemporary dentistry, zirconia protheses are processed using computer-aided design/computer-aided manufacturing (CAD/CAM). Currently, the most popular route for fabricating zirconia prostheses is to use partially sintered zirconia blanks that are produced in a semi-sintered, porous state using soft-milling techniques that make them easy to mill in a computer-assisted manufacturing (CAM) unit. However, after milling, zirconia prostheses must be sintered to reach the highest density and maximum strength. This sintering procedure is usually associated with approximately 20 to 30% volumetric shrinkage.[22] Partially sintered frameworks must be milled and enlarged by an appropriate factor in order to compensate for this shrinkage.[23] Alternatively, a less common route of fabrication uses the hard-milling technique with fully sintered zirconia. Fully sintered zirconia blanks can be milled to the exact size of the prostheses and require no supplementary sintering procedure; this is accompanied by subsequent sintering shrinkage after milling. Previous studies have reported good fitting accuracy for prostheses fabricated using fully sintered zirconia.[24] However, because of the high strength of fully sintered blanks, the main disadvantages of using fully sintered zirconia are longer milling times and increased attrition of milling tools. Additionally, fully sintered zirconia milling produces high surface temperatures that will result in surface damage and defect formation, which will significantly shorten the anticipated lifetime of the prostheses.[25]

Between 2000 and 2002, there were many reports of premature failures of total hip replacement ceramic ball heads made of yttria-stabilized zirconia that were produced by Saint Gobain Desmarquest and marketed as Prozyr. It was later determined that they failed prematurely due to changes in the processing procedure.[11,18] The sintering batch furnace was changed to a tunnel furnace that was operated using a conveyor belt to move the items faster through multiple heating chambers. Using the tunnel furnace caused a change in the sintering cycle during the cooling stage (a 3-fold reduction in the length of the tunnel furnace was made to increase the production line), which altered the microstructure and strength of the final product and consequently resulted in increased amounts of monoclinic zirconia, resulting in the unexpected clinical outcome that was observed. It became clear that subtle changes in the processing method can have drastic effects on the material and its clinical performance. The lessons learned from the higher-speed processing used for the zirconia ball heads for hip replacement should be considered during the fast processing of dental zirconia.

The most common sintering method for zirconia uses conventional furnaces at temperatures between 1350°C and 1400°C and holding times ranging from 2 to 4 hours.[26] Conventional sintering furnaces include resistively heated atmospheric furnaces but also utilize hot press and hot isostatic pressure. An alternative zirconia sintering protocol that is recommended by manufacturers using conventional ovens is a short "speed" sintering protocol (T = 1500-1600°C, t = 30 minutes) that is supposed to save time and be more economical. Several other alterative sintering methods for zirconia have been proposed that aim to improve the mechanical and optical properties of zirconia and increase the ease of operation and control of sintering energy, resulting in high productivity, safety and reliability. Among these alternative methods are spark plasma sintering,[27] microwaves,[28] and vacuum furnaces.[26]

This review is focused on the influence of alterations in the sintering parameters used for dental zirconia, including changes in the sintering time, temperature (t/T) or methods used (furnace or technique), on the microstructure and mechanical properties of zirconia. The intention was not to review all aspects of zirconia as related to its use as a dental material, but rather to provide clinicians with scientific evidence of the effects of changing sintering parameters used for dental zirconia on the microstructure, phase transformation, mechanical, and optical properties of zirconia.

2 | MATERIALS AND METHODS

2.1 | Search strategy

The search strategy involved the use of an electronic search of Embase (via OVID) and Medline (via OVID) using Boolean operators to locate relevant articles. The keywords were combined using "OR," then joined using "AND." The Medline search used the following combination of MeSH terms and keywords: (Monolithic OR Full-contoured OR Zirconia OR Zirconium OR Yttrium tetragonal zirconia polycrystalline YTZP) AND (Crown* OR Coping* OR Framework* OR Fixed Dental Prosthesis OR Full-arch Prosthesis) AND (Microstructure OR Mechanical Properties OR Flexural strength OR Optical properties OR Fracture toughness OR phase transformation OR Wear OR Low thermal degradation OR Thermal properties OR Translucency) AND (Sinter* OR Sintering OR Sintering time OR Sintering temperature OR Sintering Protocol OR Sintering method OR Sintering Technique OR Speed sintering OR Fast sintering OR Furnace OR Oven OR microwave OR Firing).

2.2 | Inclusion/exclusion criteria

Inclusion criteria were used to find in vivo and in vitro studies published during and prior to June 2018 in the English language in peer-reviewed journals that contained all or part of the keywords in their headings. The included articles were focused on the assessment of the microstructure, phase transformation, mechanical and optical properties of monolithic zirconia prostheses resulting from changes to the sintering protocol (t/Temperatures) and/or sintering methods. Studies that did not compare two or more sintering protocols or methods were excluded. Additionally, any studies that compared different sintering protocols but were not applicable to dental applications were excluded.

The electronic search was accompanied by a manual search of issues published during the last 3 years by the following journals: Journal of Prosthodontics, Journal of Prosthetic Dentistry, International Journal of Prosthodontics, Dental Materials, International Journal of Periodontics and Restorative Dentistry, Journal of Oral Rehabilitation, and Quintessence International. Additionally, the references in the selected articles were reviewed for possible inclusion. The titles and abstracts of all articles were reviewed by two independent reviewers and, upon identification of an abstract for possible inclusion, the full text of the article was reviewed and matched against the predefined inclusion/exclusion criteria.

2.3 | Extracted data

The author name and year of publication, the aim of the study, the type of zirconia used (brand name), the sample or prothesis shape and dimensions, the sintering protocol (t/T), the sintering method, and the outcome were extracted from each of the selected articles.

3 | RESULTS

The electronic search found 584 articles in Medline and 231 articles in Embase; after duplication removal and exclusion of review articles and studies in languages other than English, 198 studies remained. The titles/abstracts of the 198 studies were checked by two

TABLE 1 Summary of the 11 included articles

Author	Purpose	Outcome
Kim and Kim[37]	Effects of using different sintering techniques and various Zr thicknesses on "Optical Properties" Square specimens 22 × 22 mm	There were statistically significant differences between conventional and microwave sintering methods and thicknesses (0.5, 1.0, 1.5 mm) on **TP** (F [2, 264] = 34.257, P < .001) and the color coordinates **CIE L*** (F [2, 264] = 17.198, P < .001) and **CIE a*** (F [2, 264] = 20.724, P < .001), but not **CIE b*** (F [2, 264] = 0.989, P = .373)
Kaizer et al[35]	Effects of speed sintering on optical, mechanical, and wear characterization InCoris monolithic molar crown	Increasing the sintering temperature and decreasing the sintering time yielded smaller grain sizes and higher translucency **S** and **SS** groups exhibited a greater number of surface pits, which were associated with a greater volume and depth loss of the antagonist compared to that of the **LT** group
Sulaiman et al[39]	Effects of staining and vacuum sintering on the optical and mechanical properties of PSZ and FSZ Disc zirconia samples	For **TP** value, FSZ were significantly higher than PSZ (P < .05) regardless of the staining or the type of sintering used For **CR** values, from least to most translucent is; PSZ stained < PSZ φstain < PSZ vacuum < FSZ stained < FSZ vacuum < FSZ ϕstain For **surface gloss** value, staining increased the surface gloss of FSZ (P < .05), but had no significant effect on PSZ. Type of sintering had no effect on either of the Zr types For **F.S.** value, PSZ had higher F.S. values than FSZ (P < .05). Staining increased F.S. of FSZ, but the type of sintering has no effect. Neither staining nor the type of sintering had an effect of the F.S. value of PSZ
Ersoy et al[31]	The effects of sintering t/T on the F.S. of Zr (Bar specimen 1.2 × 4 × 25 mm, 3YTZP) In-Coris ZI and In-Coris TZI	The mean F.S. of Superspeed ZI group was significantly higher than Standard ZI and Speed ZI groups The mean F.S. of Superspeed TZI group was significantly higher than Standard TZI and Speed TZI groups A combination of a high sintering temperature with a short sintering time increased the flexural strength of zirconia
Ebeid et al[30]	Effects of changing sintering parameters on color, translucency, flexural strength Disc 15 mm in diameter Bruxzir 3Y-TZP	Increasing the sintering temperature and time for Zr did not cause any statistically significant differences with regard to hardness or flexural strength, but significantly decreased the color difference (ΔE: 4.4-2.2), contrast ratio (CR: 0.75-0.68) and roughness (Ra)
Inokoshi et al[32]	Effects of sintering conditions on LTD In-CeramYZ	Higher sintering temperatures and times increased Zr G.S., led to decreased yttrium content in the remaining tetragonal grains and made the samples having a higher monoclinic phase more susceptible to LTD
Kim et al[38]	Effects of sintering time on density, G.S. and translucency (light transmittance) 10 × 10 × 1 mm Lava frame zirconia Kavo Everest ZS-blanks	The density of Lava did not significantly differ from that of KaVo, and no significant difference in density according to sintering conditions Significant interaction was found between sintering conditions and Zr brand The longer the sintering time, the larger Zr G.S.
Stawarczyk et al[33]	The effects of different sintering temperatures on F.S., CR, and G.S. Ceramill ZI	3Y-TZP G.S. increased as the sintering temperature was increased above 1300°C, with the greatest G.S. occurring at 1700°C. The sintering temperature showed a significant negative correlation with F.S. and the CR (P < .001)
Almazdi et al[28]	Comparison of surface quality, mechanical, and physical properties between furnace and microwave methods (YTZP Emax ZirCAD)	Mean F.S. **C** 1080.08 (79.37) and **MS** 1108.33 (162.55) Density **C** 99.9 (0.22), **MS** 99.9 (0.16) Porosity size was smaller in **MS** **MS** had uniform G.S. distribution
Jiang et al[36]	Effects of sintering temperature and particle size on Zr translucency YPSZ discs	The sintering temperature and G.S. had a significant effect on light transmission (P < .001) and increasing sintering temperature from 1350°C to 1500°C increased density and translucency (light transmission)
Hjerppe et al[34]	Effects of sintering time on F.S. ICE Zirkon Disc	There was no statistically significant difference on F.S. between thermocycled (Tc-20000) and non-thermocycled (dry) Zr discs

Abbreviations: C, conventional furnace; CIELab (L* a* b*), color coordinates; CR, contrast ration; ΔE, color difference; F.S., flexural strength; FSZ, fully sintered zirconia; G.S., grain size (μ); h, hour(s); LT, long term; MS, microwave; PSZ, partially sintered zirconia; Ra, roughness; S, speed; SS, superspeed; t/T, sintering time/Temperature; T, temperature; Tc, thermocycling; TP, translucency; YTZP, yttria-stabilized tetragonal zirconia polycrystalline; Zr, zirconia.

independent reviewers, which yielded only 13 studies that were processed for full-text review based on analysis of the abstracts. Manual searches of the references of the matched articles did not provide any further articles; therefore, only articles from the electronic search were chosen. Excluded articles that did not meet the inclusion criteria were reviews, not in the English language, not in peer-reviewed journals, or did not test and compare different sintering parameters or methods of zirconia sintering and their effects on the microstructure, phase composition, mechanical, and optical properties of zirconia. Two studies were excluded because of their irrelevance to the field of dentistry.[27,29] Thus, 11 articles were ultimately selected for this review. After reading and analyzing the full texts of the 11 studies, the following factors were studied in terms of their effects on the alteration of sintering of monolithic zirconia:

1. Microstructure (grain size).[30-33]
2. Mechanical properties.[26,28,30,31,33-35]
3. Optical properties.[26,30,35-39]
4. Wear behavior.[35]
5. LTD (aging).[32]

The data extracted from the reviewed articles are summarized in Table 1. Review studies have shown that altering the sintering time and temperature (t/T), as well as the presence of impurities and stabilizer content, primarily determined the grain size and microstructure of the zirconia materials[30,32-36] These, in turn, dictated the mechanical properties and optical properties, including translucency, metastability, and resistance of zirconia to LTD.[30,32,35,37] Different methods that have been used to sinter zirconia include the use of conventional furnaces,[30,32-36] spark plasma sintering,[27] microwaves,[28,37,38] and vacuum furnaces.[26]

4 | DISCUSSION

The studies included in this review have demonstrated that altering the sintering parameters used for dental zirconia has an effect on zirconia grain size, phase transformation, and mechanical properties and optical properties, including translucency, metastability and resistance of zirconia to LTD.[30,32,35,37]

4.1 | Effect of altering sintering time/temperature on the optical properties of zirconia

The esthetic characteristics of a zirconia restoration are related to its optical properties, which include translucency, contrast ratio, color, direct transmittance of light, and opalescence. As previously discussed, different methods have been attempted to increase translucency of zirconia. The elimination of light-scattering alumina sintering aids porosity and improves translucency but also requires a higher sintering temperature (1530°C) in conjunction with a longer dwell time (6 hours), as in second generation zirconia. These changes, in turn, decrease the hydrothermal aging resistance of zirconia.[40] Another method of improving translucency involves increasing the Y_2O_3 content and sintering temperature and/or sintering duration. The translucency of zirconia is additionally influenced by the ceramic brand and thickness,[26] ceramic shade, primary grain size, refractive index, atmospheric conditions while sintering, surface roughness, contrast ratio, acidic medium, and staining,[41] whereas the contrast ratio is affected by the zirconia brand and thickness, grain size, sintering temperature and duration, and translucency.[26] Color is affected by the number of firings, ceramic brand, ceramic thickness, cement color, cement thickness, abutment color, sintering temperature and duration, and number of coloring liquid applications.[41] Opalescence is affected by the number of coloring liquid applications and the ZrO_2 and Y_2O_3 concentrations used.

A recent study investigated the optical characterization of InCoris TZI Sirona monolithic translucent molar zirconia crowns produced using three sintering protocols: a long-term protocol (LT) conducted at 1510°C for 4 hours, a speed (S) protocol conducted at 1510°C for 60 minutes, and a superspeed (SS) protocol conducted at 1580°C for 10 minutes.[35] The authors found that the use of different sintering protocols significantly affected the grain size, translucency, hardness, and wear behavior of the antagonist. Increasing the sintering temperature and decreasing the sintering time yielded smaller grain sizes and higher translucency. The SS group exhibited the highest translucency among the three groups. This study appears to be more clinically relevant, as monolithic zirconia crowns were used.

Another study examined the roughness of monolithic zirconia after sintering at 1460°C, 1530°C and 1600°C using 1-, 2-, and 3-hour holding times[30] They found significant decreases in the color difference (ΔE: 4.4-2.2), contrast ratio (CR: 0.75-0.68) and roughness (Ra) as the sintering temperature was increased. A mean ΔE value less than 3.0 is considered clinically imperceptible, a value of 3 to 5 is clinically acceptable, and a value greater than 5 is considered clinically unacceptable. When the CR is 0, the zirconia is considered to be most transparent, while zirconia with a CR of 1 is considered the most opaque. According to this study, all three different sintering parameters yielded clinically acceptable results, and increases in temperature allowed the zirconia to gain more translucency but still appear opaque.[30] This result could be attributed to the fact that increasing the sintering temperature reduced porosity, increased the density and, consequently, produced less light scattering and more light transmission.

Another study used 3 mol% Yttria PSZ (second generation zirconia) discs/cylinders with two different initial zirconia particle sizes (40 vs 90 nm) and four sintering temperatures (1350°C, 1400°C, 1450°C, 1500°C)[36] and found that the sintering temperature and grain size had a significant effect on light transmission ($P < .001$) and increasing sintering temperature from 1350°C to 1500°C increased density and translucency. Therefore, it is clear that increasing the sintering temperature and decreasing the sintering time yields better translucency in sintered dental zirconia ceramics.

It has been documented in the literature that as the aging time is increased, the transparency decreases and the ceramic material becomes more opaque (higher contrast ratio), darker, reddish, and yellowish.[41] It is also well known that aging zirconia roughens its surface by increasing the growth of the transforming monoclinic phase and the corresponding surface relief. [41]

The sintering zirconia using microwaves is poorly addressed in the existing dental literature. A few studies have tried to evaluate the effects of using microwave sintering parameters on the optical properties of zirconia and to compare this method to conventional sintering techniques, but no clear conclusion has emerged from these comparisons.[28,37,38] Kim et al[38] compared the optical properties of three different thicknesses of monolithic zirconia that were sintered using a conventional oven for 2 hours and a microwave oven for 30 minutes at 1500°C and found that there were statistically significant differences in the effects of the different sintering methods and thicknesses on the color coordinates CIE L* and CIE a*, but not CIE b*; the reduced processing time used during microwave processing yielded similar color perception and translucency, as did the use of a conventional sintering technique.[37] However, the color difference (ΔE_{00}) between the shade table A2 and each subgroup was measured, and the average color difference was between 7.20 and 10.32 units, which is considered clinically unacceptable based on previous studies.[42,43] Scanning electron microscope analysis found that a slightly smaller grain size range (100-250 nm) resulted from the conventional sintering than the microwave sintering (250 nm).[28] Atomic Force Microscope (AFM) analysis yielded a Ra value of 0.054 μm for conventional sintering and 0.034 μm for microwave sintering. The uniform pack appearance in the microwave samples could be attributed to better specular reflection and a higher color value compared to that resulting from conventional sintering. A higher monoclinic phase content resulted from both sintering methods, and different amounts were found for different thicknesses. Almazdi et al[28] found that using microwave sintering yielded zirconia with reduced porosity and a uniform grain size distribution. On the other hand, Kim et al[38] focused on evaluating the translucency of two commercial zirconia brands (Lava and Kavo) and found that, despite the fact that there were no significant differences in density resulting from different sintering conditions, decreasing the sintering time resulted in smaller grain size and consequently increased the translucency; these results suggest that the interaction between the sintering method used and zirconia thickness have a significant effect on translucency.[37]

4.2 | Effect of altering sintering time/temperature on the mechanical properties of zirconia

Reviewing the selected studies in terms of the zirconia types used, it has been observed that different zirconia types have different microstructures, particle sizes, porosity, size distribution, additive types and concentrations, and different raw material compositions. In addition, the microstructures within a single blank can be heterogeneous. From a mechanical perspective, one study found that significantly increasing the sintering temperature and time for zirconia material (Bruxzir 3Y-TZP) did not cause any statistically significant differences with regard to hardness or flexural strength, although it significantly enhanced translucency and color reproduction.[30] Another study showed that the grain size of 3Y-TZP zirconia increased as the sintering temperature was increased above 1300°C, with the greatest grain size occurring at 1700°C, and the that sintering temperature showed a significant negative correlation with flexural strength and the contrast ratio ($P < .001$).[33] In contrast, another study showed that a combination of a high sintering temperature with a short sintering time increased the flexural strength of zirconia,[31] but no further analysis of the results was provided. Therefore, the results so far are inconclusive in regard to the relationship between increased sintering temperature and flexural strength.

The effect of full zirconia restorations on the wear of antagonistic teeth is an issue of great clinical significance.[44] The wear behavior of any material is a complex phenomenon and can be affected by many factors, including patient-related factors such as dietary habits, dysfunctional occlusion, masticatory forces and bruxism, as well as material type, fracture toughness, internal pores, surface flaws and/or defects in the microstructure, physical properties and surface texture (finishing and polishing of the restoration surface), and environmental factors.[44] Kaizer et al[35] studied the effects of speed sintering (LT, S, and SS; as mentioned above) on the wear behavior of monolithic zirconia crowns. The authors found that areas of mild and severe wear were observed on the zirconia surface in all groups. However, micropits in wear craters were less frequent in the LT group, while the S and SS groups exhibited a greater number of surface pits, which were associated with a greater volume and depth loss of the antagonist compared to that of the LT group. The authors also found that the $t \rightarrow m$ phase composition was related to the wear crater; this, in turn, raised concerns regarding the adjustment of occlusion when delivering monolithic zirconia prostheses, especially in cases where speed and superspeed sintering protocols and chairside technologies have been utilized. Although it appears that speed sintering yielded poorer wear behavior than long-term sintering, more studies are needed to produce a conclusive statement.

In addition to finding that increasing aging time decreased transparency,[41] Burgess et al[45] also found that aging zirconia for 5 hours in a dental autoclave at 135°C and 2 bar pressure increased its roughness, but not by a statistically significant amount; no increase in opposing enamel wear noted was noted. Additionally, Scanning Electron Microscope (SEM) analysis showed that it had a similar surface smoothness as non-aged zirconia. It should be noted that this was an in vitro study, therefore, application of the results to clinical situations should be cautioned against. Inokoshi et al[32] found that higher sintering temperatures and longer sintering times increased zirconia grain size, which led to decreased yttrium content in the remaining tetragonal grains and a higher monoclinic phase content; such materials are more susceptible to the effects of aging. Sintering in a vacuum furnace appears to improve the flexural strength of zirconia. However, vacuum sintering also significantly enhances the translucency of partially sintered zirconia and has no significant effects on fully sintered zirconia.[26]

Because there are many approaches used to determine translucency in the dental literature[46]; the contrast ratio,[47] transmission coefficient[48] and translucency parameter (TP),[49] caution has to be taken when comparing translucency between studies without establishing uniform critical factors. The major factors affecting translucency include specimen thickness, the reflectance parameters of the black and white backings, and optical contact.[50,51] Therefore, comparison at established thickness, backing and optical contacts are recommended.

5 | CONCLUSIONS

Alteration of sintering parameters has been found to alter the microstructural, mechanical and optical properties of zirconia. Increasing the sintering temperature and decreasing the sintering time improves light transmission and decreases the contrast ratio, and therefore enhances the optical properties of zirconia. The reviewed results were, however, contradictory regarding the effects of changes in sintering time and temperature on the flexural strength of zirconia. While alteration of the sintering parameters and methods would be expected to alter the wear behavior of monolithic zirconia and its effect on antagonistic surfaces, more studies are needed to confirm these effects. It is crucial for dental professionals, including both clinicians and technicians, to be aware of the source of zirconia materials and processing techniques and the related mechanical and optical properties, as well as proper handling, since all zirconia blanks are not the same and a single zirconia blank can have variations in its microstructure. In summary, increasing the sintering temperature and decreasing the sintering time improved the translucency of zirconia in in vitro studies but also had negative effects on its mechanical behavior. Therefore, we would expect that the clinical performance of monolithic zirconia restorations would be influenced by alterations in the methods and/or parameters used for sintering. Finally, there is a lack of comprehensive clinical studies regarding the influence of altering sintering parameters or fabrication methods on the performance of monolithic zirconia restorations, and further investigation in the future is encouraged.

DISCLOSURE OF INTEREST

The authors do not have any financial interest in the companies whose materials are included in this article.

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