

Optical Behavior of Zirconia Generations

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Abstract

The lack of a glassy matrix in the crystalline structure causes high opacity in 3 mol% yttria-doped tetragonal zirconia polycrystals (zirconia generation I). Physically, it has a high refractive index, which leads to high amounts of total reflection. The orientation of tetragonal crystals can cause birefringence, which alters the refractive index. This high reflection tends to produce a mirror-like surface, thereby leading to poor esthetics. To overcome this drawback, zirconia-generation I was veneered with feldspathic ceramics. However, the frequent occurrence of catastrophic failures in veneered ceramics has culminated in the emergence of monolithic zirconia. However, there has been a lack of study into the optical properties of contemporary zirconia generations; thus, the purpose of this review article is to examine light patterns in non-metallic materials, define zirconia generations based on their optical qualities, and explore the parameters that influence the optical properties of zirconia ceramics.

Keywords: Zirconia, translucency, contrast ratio, optical properties

INTRODUCTION

Zirconia, which is a bioinert polymorphic ceramic, has become a popular restorative material owing to its advantageous features, such as chemical inertness, superb biocompatibility, low tendency for bacterial adhesion, and a coefficient of thermal expansion comparable to enamel and dentine.¹ However, it is extremely hard (Vickers: ~12.7 GPa),² with a high melting point (~2690 °C),³ modulus of elasticity (~210 GPa),⁴ and high opacity.^{5,6}

It displays 3 distinct crystallographic forms [monoclinic (M), tetragonal (T), and cubic (C)-phases], known as allotropism, in dependence on temperature and preserves its T-phase at room temperature owing to its stabilization with alloying metal oxides such as yttrium oxide. The transformations among these allotropes are martensitic and a-thermal.^{5,7,8} When it is stressed, T→M (transformation from T- to M-phase) occurs, which is related to a volumetric increase (4.5%). This compresses the crack flaws and inhibits further propagation, thereby exhibiting superior mechanical service (transformation-toughening trait).^{9,10} Although 3 mol% yttria-doped tetragonal zirconia polycrystal (3Y-TZP) remains a popular choice, numerous other polycrystalline zirconia materials have emerged for dental applications.

Studies on the optical characteristics of zirconia generations are scarce. This article aims to scrutinize light patterns in non-metallic materials, define zirconia generations and their optical properties, and discuss the parameters that influence the optical properties of zirconia ceramics.

Light Patterns in Non-Metallic Materials

When light hits a polycrystalline material, some of it passes through (transmission), some reflects off the surface because of its surface roughness, and some is either scattered or absorbed within the material.¹¹⁻¹³

The light transmission qualities of non-metallic materials are affected by electronic polarization and electron transitions between the valence and conduction bands. These materials with varying bandgaps might appear opaque, opaque-colored, or transparent-colored.^{12,14,15} Non-metallic materials with bandgaps greater than 3.1 eV are typically transparent to light. However, electrical polarization can cause minimal light absorption, resulting in a translucent appearance and diffuse light transmission.^{12,15}

The transmittance of light is affected by three parameters: the absorption coefficient, scattering coefficient, and scattering anisotropy

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factor of the material.¹⁶ The scattering anisotropy factor is the average scattering angle value, which measures how much light is forward scattered (translucency) or backward scattered (opacity) during a single scattering event. The higher the number of scattering events, the more homogeneous the transition of light from anisotropic to isotropic.^{12,15} The transport coefficient is calculated by adding the absorption and scattering coefficients, which attenuate the transmitted light. Non-ideal materials have a reduced scattering coefficient, which combines the three aforementioned parameters. The reduced scattering coefficient denotes the proportion of forward-scattered light without absorption. Longer wavelengths in zirconia lead to more forward-scattered light in the visible spectrum.^{12,15,16} It can be highlighted that multiple internal and external parameters can influence the optical properties of zirconia ceramics.^{11,15,17,18} Zirconia exhibits low translucency with elevated opacity. The contrast ratio of zirconia was estimated at 1.¹⁹

Zirconia Generation

Generation I

The first generation of polycrystalline zirconia (3Y-TZP) has been successfully used for years in the fabrication of all-ceramic restorations.^{9,20} The components like yttrium oxide ($4.5 < x \leq 6$ wt%), hafnium oxide or hafnia (≤ 5.0 wt%), aluminum oxide or alumina ($0.5-1.0$ wt%), and other oxides (calcium oxide and magnesium oxide) (≤ 1.0 wt%) are incorporated into the zirconium oxide lattice ($88-95.5$ wt%).²¹ The yttrium III ion has a radius of 104 pm, which is significantly larger than that of the zirconium cation (86 pm). Although this results in significant distortion, the yttrium III ion is related to C structure stabilization.^{22,23} Hafnium oxide is isomorphic to zirconia, and the crystal ionic radius of hafnium ion (85 pm) is nearly identical to the radius of quadrivalent zirconium (86 pm), allowing for optimal solid solubility.²⁴ Alumina is often employed in formulations, although its solubility in zirconia is poor due to aluminum cation's short ionic radius of ~ 68 pm.²⁵ This inclusion increases densification during sintering, potentially by enhancing ion mobility, and it also has favorable effects on fracture toughness when the concentration is kept low. It is also helpful to reduce the detrimental low-temperature degradation (LTD).^{11,26} The sintered 3Y-TZP material contains nearly 98% metastable T-phase.²⁷

Because 3Y-TZP is partially stabilized although it is in the T-phase at room temperature, its internal structure contains energy to transform into the M-phase.²⁸ If 3Y-TZP is subjected to stress or any force, cracking occurs in its structure; T-crystals begin to shift to the M-phase and a 3-5% increase in volume occurs. This volume increase prevents crack progression by creating compressive stresses. This phenomenon, namely "transformation toughening", provides superior mechanical properties to 3Y-TZP.^{15,29,30} The typical grain size is reported as 0.5 μm and the aforementioned martensitic transformation depends on the grain size.¹⁵ The grain size determines the stability and mechanical properties of zirconia ceramic.³¹ High sintering temperatures and long sintering times cause particle sizes to increase.⁸ When the grain size is less than the critical size (< 0.3 μm), zirconia loses its capacity to T \rightarrow M during crack propagation, resulting in lower toughness.^{15,32}

Zirconia ceramics are also susceptible to LTD, which can be accelerated by processing procedures, humidity, stress, and low temperatures (200-300 °C). Because yttrium is triatomic and contains oxygen vacancies, water can enter the zirconia lattice a hygroscopic medium.³³ Initially, this diffusion can produce lattice contraction, which concentrates tensile stresses on the surface of the zirconia grains, causing the

T \rightarrow M. This generates micro-fissures, which allow water molecules to penetrate further into the innermost grains, and therefore T \rightarrow M of the superficial layer advances deeper into the bulk of the material, creating macro-cracks. This phenomenon may be influenced by grain size, the proportion of stabilizer, residual tension, and manufacturing flaws.³³⁻³⁵

3Y-TZP restorations also exhibit high opacity due to the lack of a glassy matrix in the crystallographic structure.^{29,36} From a physical perspective, it has a high refractive index, resulting in high total reflection. The orientation of T-crystals can generate birefringence, which leads to changes in the refractive index (Figure 1).^{8,9} This high reflection tends to produce a mirror-like surface that causes poor esthetics. This can be explained by the T grains, which are optically anisotropic.^{11,26,37,38} Moreover, a high amount of small crystalline grains, possible pores, and precipitated aluminum oxide lead to a further deterioration in translucency by forming excessive interfaces that act as scattering zones.^{11,18,39} To circumvent these poor esthetic characteristics, it has been suggested to be used only as a coping in fixed prosthetic restorations and to be veneered with low-fusing feldspathic porcelain (bilayer manner).^{8,29,40} Although several catastrophic complications including cracking, chipping, and delamination have been reported; these restorations have been produced in this manner for decades, up until 2014.^{29,41} The main reason for these complications is the difference in thermal expansion coefficient between zirconia and low-fusing feldspathic porcelain, followed by firing shrinkage, poor wetting, overloading, fatigue, and insufficient coping design.^{8,41}

With the development of full-contour (monolithic) zirconia restorations that do not require veneering (monolayer manner), an important contribution has been made to eliminating catastrophic complications.^{29,41} Moreover, these restorations save dental tissue, provide superior fracture resistance, and can be preferred in patients with limited inter-occlusal space, as only a 0.5 mm occlusal thickness is sufficient to withstand high masticatory forces.⁴¹ Different ways for individualizing restoration, such as embedding in coloring liquids, the addition of metallic pigments to the preliminary zirconia powder, or painting zirconia with liners, are in use; however, the optical properties of these restorations were still unsatisfactory, and new generations were necessary.⁸ In the past 10 years, serious progress has been made, and manifold zirconia materials offering different optical and mechanical characteristics, concerning differences in their chemistries and notably stabilizer content, have been developed (Table 1)^{8,38}.

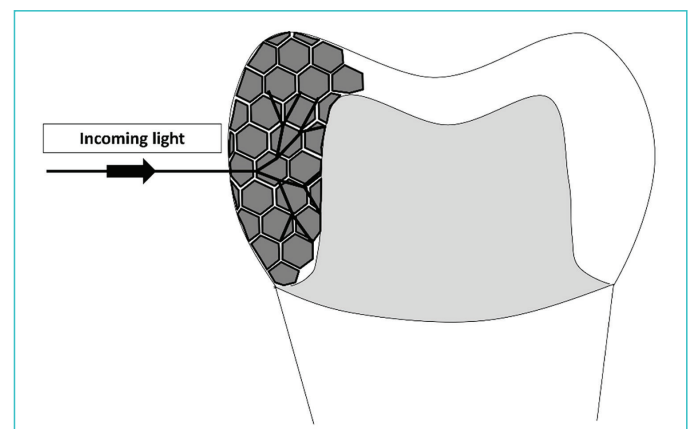


Figure 1. Light patterns of zirconia.

Generation II

The studies carried out on new-generation zirconia ceramics have been aimed at obtaining a more esthetic and translucent material without compromising superior mechanical properties as much as possible.⁴² The 2nd generation (3Y-TZP with modified alumina content) has been introduced, which shows the same amount of yttria as the first generation 3Y-TZP. However, the 2nd generation 3Y-TZP exhibits some difference in the degree of light transmittance by reducing the aluminum oxide content from 0.25 to 0.05% by weight and also by reducing the aluminum oxide particle sizes and repositioning them at the zirconia grain boundaries.^{20,43-46} With this modification, the aluminum oxide ratio fell below 0.05%. It has been observed that although this attempt slightly weakens the mechanical properties by making the T-phase of the material less stable, causing it to be more sensitive to LTD; it also contributes to a slight increase in translucency.^{42,43,47}

Another approach to improve zirconia translucency involves the addition of 0.2 mol% lanthanum (III) oxide to the material.^{5,47} The addition of lanthanum (III) oxide to 3Y-TZP improved translucency but weakened the mechanical properties.⁷ In studies investigating approaches in which the aluminum oxide or lanthanum (III) oxide contents in zirconia are modified while the amount of yttrium oxide (3 mol%) remains constant, it has been observed that translucency is still insufficient for anterior restorations.^{5,7}

Generation III

5Y-TZP subgeneration

The increasing demand for esthetics has led to the development of 3rd generation zirconia-based ceramics, in which the C-phase content of the material is increased by adding a greater amount of stabilizing oxide.⁹ Third-generation zirconia was introduced in 2015 and thus fulfilled the esthetic desire expected from the material with its high yttria content of 5 mol%.^{8,38,43}

4Y-TZP subgeneration

Since the 5Y-TZP sub-generation could not meet the desired mechanical requirements in long-span restorations, a 4 mol% yttria-stabilized (4Y-TZP) material with an approximately 30% C-phase content proportional to T-phase content was developed as a middle point between the second generation and 5Y-TZP sub-generation.^{43,48} Translucent zirconia containing 4 or 5 mol% yttria has a flexural strength of 600-900 MPa and a fracture strength of 2.2-4.0 MPa(m).⁴⁹

>5Y-TZP subgeneration

They have a larger yttrium oxide concentration and hence more C-phase in proportion to the T-phase, which renders the structure more stable and resistant to hydrothermal aging, making it less vulnerable to LTD.^{8,11,43,50} The key explanation for the increased translucency is the isotropic feature of the C-phase, which reduces the optical scattering coefficient and inhibits the birefringence of the current T-phase.^{43,51} This characteristic means that the incoming light is spread more evenly in all spatial directions.⁸ The translucency is also affected by the microstructure. The fact that C-crystals have a larger volume than T-crystals results in a decrease in the number of grain boundaries, which improves the translucency properties of the material.⁴⁸ The higher the sintering temperature and yttria content, the higher the C-crystal phase ratio in zirconium dioxide.⁴³ In addition to improved optical properties,

the fact that the material contains C-crystals in a stable structure results in a lower or no transformation toughening ability, which occurs with the T→M as a result of tension, resulting in disadvantages such as a decrease in the flexural and fracture strength of the material.^{43,45,52} Carrabba et al.⁵⁰ Observed an inverse relationship between resistance and translucency in zirconia ceramics.

Generation IV

As a solution to improving the esthetic properties of monolithic zirconia restorations with a monochromatic structure, 4th generation multi-layer/multi-chromatic zirconia blanks consisting of layers with different tones and translucency gradients have been developed.^{9,18} While translucency/color transition creates a masking effect in the cervical region, it imitates the optical properties of dentin tissue in the middle region and enamel tissue in the incisal region. Multi-layer/multi-chromatic zirconia blanks can have three or four different tone layers (enamel, first transition, second transition, and dentin or body).^{18,53} From the cervical to the incisal regions, tones can have up to seven layers and a visible light transmittance percentage of 44% to 49%.¹⁸

Parameters Influencing the Optical Characterization of Zirconia

The optical characteristics of zirconia restorations are influenced by both intrinsic (fabrication process) and extrinsic (laboratory procedures and clinical variables) factors.^{15,17,18} While fabrication processes dictate the basic optical properties of zirconia ceramics, diverse laboratory operations performed on zirconia ceramics may result in optical alterations in the material (Figure 2).^{18,54}

Intrinsic Parameter 1: Blank Fabrication

During the fabrication, some parameters, such as the chemical purity of the powder, type of pressing applied, particle properties, additives added to the structure, and pre-sintering process applied, have a very important effect on determining the final optical properties of the material.³⁹

Intrinsic Parameter 2: Microstructure

Y-TZP optical performance can be improved through a variety of microstructural modifications, including increasing the yttria content, lowering or eliminating aluminum oxide doping, improving the sintering conditions, minimizing residual porosities, and producing a nanometric microstructure.²⁹

Intrinsic Parameter 3: Particle Size and Grain Boundary Effect

In the light spectrum, the wavelength of visible light is between 300 and 700 nm, and in daylight it is approximately 555 nm. The largest scattering is recorded when the particle size is similar to the wavelength of visible light.³⁹ When the particle size and light wavelength are in close range; as the particle size increases, light scattering will increase and the translucency of the material will decrease. However, if the particle size is much larger than the wavelength of light, scattering decreases as the particle size rises, independent of wavelength.^{18,39,54} Materials containing particles smaller than approximately 0.1 μm appear more translucent due to less reflection and absorption when exposed to visible light wavelengths than materials containing larger particles.^{32,39} On the other hand, in materials with particle sizes larger than 10 μm , light encounters fewer grain boundaries because of the low number of particles in unit volumes, and less light reflection occurs, thus reducing opacity.³⁹ While translucency is provided by high diffusion transmission

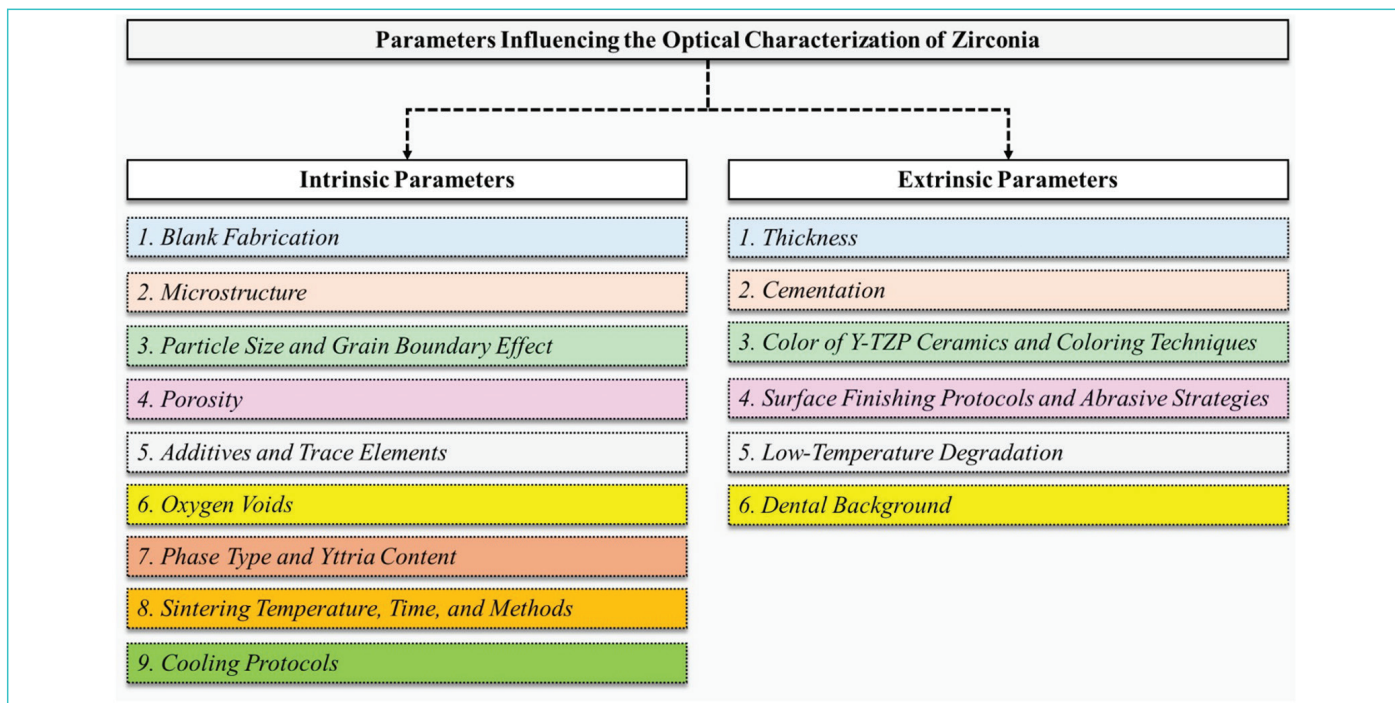


Figure 2. Parameters influencing the optical characterization of zirconia.

in materials with large particle sizes; in materials with small particle sizes, high in-line transmission is achieved.⁵⁵ When particle diameters are between 0.01 and 0.1 μm , translucency is provided by in-line transmission, and the material exhibits a translucent to transparent appearance. While grain boundary scattering is observed at particle diameters of 0.1-1.0 μm , diffuse transmission is observed at particle diameters of 1-10 μm and the material is largely translucent.^{39,56}

Intrinsic Parameter 4: Porosity

Porosities can be intergranular or intragranular and exhibit different optical properties from each other.^{12,15} Intergranular porosities are the porosities between particles with different orientations and are typically considered as amorphous defect regions in the form of voids located in different directions on the grain boundaries between two or three crystalline particles. Intragranular porosities are porosities found within the particles and represent separate interfaces between two effective isotropic phases.^{11,12,15} Reducing the particle size tends to reduce the porosity size proportionally. In addition, with smaller particle sizes, it becomes easier to remove the gas trapped in the intragranular porosities, thereby preventing the removal of the porosities.¹² Partial or complete elimination of porosity occurs during condensation, which is driven by ionic diffusion at high temperatures.¹⁵

Intrinsic Parameter 5: Additives and Trace Elements

Additives in Y-TZP ceramics, such as aluminum oxide, scandium oxide, neodymium oxide, lanthanum (III) oxide, magnesium oxide, hafnium oxide, sodium oxide, silicon dioxide, iron oxide, calcium oxide, yttrium oxide, and germanium oxide, that can be used as oxides can cause segregation on the grain boundaries of zirconium dioxide and can affect the translucency of the material.^{7,15,39} It is known that aluminum oxide added to the structure of zirconia helps the chemical stability of zirconia, minimizes the LTD potential that may occur in the oral

environment, reduces the required sintering temperature and time, and increases the densification of Y-TZP ceramics by creating fine-particle and homogeneous microstructures.^{11,26} On the other hand, aluminum oxide and zirconium dioxide have different refractive indices and the presence of aluminum oxide inclusions, which are accepted as important scattering centers by increasing light scattering between the two materials; it causes the zirconia material to show low translucency. Therefore, it has been suggested to eliminate aluminum oxide or reduce its concentration to increase translucency.^{11,18} The refractive indices of aluminum oxide and zirconium dioxide at 600 nm wavelength are 1.77 and 2.22, respectively.^{11,18,57} Developers focused on increasing translucency by reducing the aluminum oxide content from 0.25% to less than 0.05% and minimizing light refraction.^{5,11,26} Although it was observed that reducing aluminum oxide below 0.25% by weight prevented the formation of particles acting as light scattering centers; it has been suggested that, due to the advantageous properties of aluminum oxide in its material structure, completely removing it from the structure is not a good option. In addition, studies have shown that zirconia without aluminum oxide does not show any difference in translucency compared to zirconia with reduced aluminum oxide content and that only reducing the amount of aluminum oxide rather than completely removing it from the structure is sufficient to produce a more translucent material.⁹

Zhang et al.⁵⁸ Devised a different method for creating zirconia that is highly translucent, strong, and resistant to aging. Compared with quadrivalent zirconium, trivalent ions with larger radii were considered to be additives. Researchers reported that trivalent additives such as lanthanum cations from lanthanum (III) oxide added to quadrivalent zirconium exhibited significant segregation at the zirconium dioxide grain boundary. The use of lanthanum (III) oxide as an auxiliary doping oxide increases the possibility of obtaining a microstructure with smaller particles and improves optical properties due to the

small particle size, narrow grain boundary width, and reduction in birefringence.^{39,58} The incorporation of lanthanum (III) oxide (0.2 mol%) into standard aluminum oxide (0.1-0.25 wt%) doped 3Y-TZP yielded an average translucency, better hydrothermal stability, and excellent mechanical characteristics.^{11,39} On the other hand, the addition of 0.2 mol% lanthanum (III) oxide to 0.1 wt% aluminum oxide-doped Y-TZP significantly improved the translucency.¹² Researchers observed that adding 0.2 mol% lanthanum (III) oxide to 0.1 wt% aluminum oxide-doped 3Y-TZP resulted in 42% higher translucency compared to conventional 0.25 wt% aluminum oxide-doped 3Y-TZP.³⁹

Transition and rare-earth metals can be used in the composition of additives because they give color tones to colorless oxides. The study on zirconia color improvement has focused on the influence of incorporating ferric oxide or employing 3Y-TZP nanopowders on the microstructure and mechanical characteristics.^{12,15} A study examining

the mechanochemical processing of praseodymium-doped 3Y-TZP nanopowders showed that this additive is promising, exhibiting good esthetic results and biocompatibility. Since zirconium ions are tetravalent, divalent, or trivalent (e.g. trivalent yttrium, divalent iron, trivalent iron (added to the structure to prevent the T→M), divalent nickel, trivalent chromium); positively charged stabilizing additives must be charge-balanced. The value, concentration, ionic radius, and applied sintering temperature of the additives added to the zirconia structure can affect the defect distribution, defect stability, and therefore optical properties.¹²

Intrinsic Parameter 6: Oxygen Voids

Since the value of quadrivalent zirconium is smaller than that of yttrium (III) ions added to the structure for stabilization, oxygen voids are formed within the structure, and when the amount of these

Table 1. Commercial examples of zirconia from different generations

Material	Generation					Brand
	3Y-TZP	4Y-TZP	5Y-TZP	>5Y-TZP	ML/MC	
Ceramill zolid FX	-	-	-	5.3-5.5%	5-5.5%	Amann Girrbach
Prettau 4 Anterior	-	-	-	7%	-	Zirkonzahn GmbH
Prettau 4 Anterior Dispersive	-	-	-	-	7%	Zirkonzahn GmbH
Lava Plus	3%	-	-	-	-	3M ESPE
Lava Esthetic Zirconia	-	-	5%	-	-	3M ESPE
IPS Emax ZirCAD Multi	-	4%	-	-	4-5%	Ivoclar Vivadent Inc.
VITA YZ HT	3%	-	-	-	-	VITA Zahnfabrik
VITA YZ ST	-	4%	-	-	4%	VITA Zahnfabrik
VITA YZ XT	-	-	5%	-	5%	VITA Zahnfabrik
CopraSupreme	-	4%	-	-	4%	Whitepeaks
CopraSmile	-	-	-	5.4%	5.4%	Whitepeaks
CopraSmile Symphony	-	-	4.8-5.3%	-	4.8-5.3%	Whitepeaks
CopraSupreme Symphony	-	4%	-	-	4%	Whitepeaks
Zenostar T	3%	-	-	-	-	Wieland Dental
Zenostar MT	-	4%	-	-	-	Wieland Dental
DD Bio ZX ² - HT	3%	-	-	-	-	Dental Direkt GmbH
DD cube ONE- HT ⁺	-	4%	-	-	-	Dental Direkt GmbH
DD cubeX ² SHT	-	-	5%	-	5%	Dental Direkt GmbH
Cercon HT	3%	-	-	-	3-5%	Dentsply Sirona
Cercon XT	-	-	5%	-	5%	Dentsply Sirona
inCoris TZI	3%	-	-	-	-	Dentsply Sirona
BruxZir Full Strength	3%	-	-	-	-	Glidewell Direct
BruxZir Esthetic	-	4%	-	-	-	Glidewell Direct
BruxZir Anterior	-	-	5%	-	-	Glidewell Direct
KATANA Zirconia HT & ML	3%	-	-	-	3%	Kuraray Noritake Dental Inc.
KATANA Zirconia HTML Plus	-	-	5%	-	5%	Kuraray Noritake Dental Inc.
KATANA Zirconia STML	-	4%	-	-	4%	Kuraray Noritake Dental Inc.
KATANA Zirconia UTML	-	-	5%	-	5%	Kuraray Noritake Dental Inc.
KATANA Zirconia YML	-	-	-	-	3-5%	Kuraray Noritake Dental Inc.
Shofu Disk ZR Lucent	-	-	5%	-	-	Shofu Inc.
Shofu Disk ZR Lucent Supra	-	-	-	-	3-5%	Shofu Inc.

Data was collected from the manufacturers' websites and brochures. HT: High translucent, ST: Super translucent, XT: Extra translucent, T: Translucent, MT: Medium translucent, HT⁺: High translucent plus, SHT: Super high translucent, ML: Multi-layer, HTML: High translucent multilayered, STML: Super translucent multilayered, UTML: Ultra translucent multilayered, YML: Yttria multilayered, ZR: Zirconia.

voids increases, defect clusters that damage optical performance may occur.^{12,47} Moreover, uncontrolled heating or sintering processes performed in an environment in which reactions are reduced have a significant effect on the formation of oxygen voids. They serve as light-scattering centers within the structure and reduce the translucency of the material. Therefore, it is important to control the heat treatment to reduce the number of oxygen voids in the material.^{18,39}

Intrinsic Parameter 7: Phase Type and Yttria Content

Unstable zirconia crystal structures change with temperature.⁷ The M-phase can act as a defect in the zirconium dioxide microstructure, and these defects can reduce translucency by increasing the scattering of incoming light.³⁹ The addition of stabilizing oxides to unstable zirconia can limit phase transitions and help stabilize the material in the C- or T-form at room temperature.⁷ Conventional 3Y-TZP consists of 5.18% yttria (3 mol%) by weight and 90% or more of the T-phase.^{18,47} The birefringence of T zirconia, as well as its anisotropic refractive index in distinct crystallographic directions, limit the material's light transmittance by causing reflection and refraction at grain boundaries.²⁶ A new approach to increasing the translucency of zirconia has been determined to develop a new generation of zirconia materials with an isotropic C-phase, which reduces light scattering from birefringent grain boundaries.^{5,32} Higher yttrium oxide content tends to increase the amount of the optically isotropic C-phase in the zirconium dioxide structure, which makes light scattering at grain boundaries less critical, regardless of particle size, and improves optical properties by increasing translucency.^{7,11,58} Cho et al.¹⁰ reported that the increase in yttria (mol%) in the zirconia material significantly increased the TP value, and 5Y-TZP exhibited approximately 80% translucency at a thickness of 0.8 mm and approximately 89% translucency at a thickness of 1.5 mm, compared to lithium disilicate. An average particle size of less than 0.08 μm , 75% T - 25% C-phase content, and a porosity amount of less than 0.01% enable the fabrication of zirconia ceramics with translucent character. Increasing the C-phase content up to 50% increased the translucency to ultrahigh levels. However, both the decrease in particle size and the increase in the C-phase ratio reduce the flexural and fracture strength of zirconia.^{9,18} From a general theoretical approach, 8 mol% yttria content provides complete stabilization of C-phase zirconia; 4-5 mol% yttria content (4Y-PSZ, 5Y-PSZ) provides partial stabilization (50%) of C-phase zirconia.^{26,47} The combination of a small particle size with isotropic C zirconium dioxide provides translucency comparable to that of lithium disilicate.^{7,39} Although it is a common finding in many studies that zirconia ceramics containing high amounts of yttria exhibit enhanced translucency properties; the effect of varying yttrium oxide content on the translucency of new-generation zirconia ceramics was reported by Inokoshi et al.⁵⁹ In a recent study. In the results obtained, the increase in the yttrium oxide content was associated with an increase in the C-phase and, consequently, an increase in translucency.

Intrinsic Parameter 8: Sintering Temperature, Time, and Method

Studies examining the effect of sintering temperature on the optical properties of zirconia have reported an increase in translucency and a decrease in contrast ratio due to the increase in density in the material as a result of the increased particle size and reduced porosity caused by high sintering temperatures. The optimum sintering temperature for monolithic zirconia is generally between 1400-1550 °C; At temperatures exceeding 1600-1700 °C or after long-term sintering procedures, grain boundary cracks that increase light scattering may occur in

the material.¹¹ Kim et al.⁶⁰ reported that an increase in the sintering temperature (from 1350 °C to 1550 °C) reduced the porosity, making the polycrystalline structure of zirconia more compact, and reducing the sintering duration resulted in materials with smaller particle sizes and higher translucency. Ebeid et al.⁶¹ Observed that higher temperatures (1600 °C) and longer waiting times (4 hours) led to higher translucency. Additionally, compared to its conventionally sintered equivalents, the rapid-sintered monolithic Y-TZP exhibits greater volume loss, which could impact the material's translucency over time. When the outer surface of Y-TZP is subjected to heat and the heat moves into the core, strong temperature gradients and internal tensions are produced, resulting in particle growth. Microwave sintering guarantees that the material is heated quickly and evenly both internally and externally, and particle coarsening is avoided by operating at a reduced temperature range during the operation. Thus, a final product with higher density, uniformity, and smaller particle sizes is obtained. As a result, Y-TZP ceramics sintered by the microwave sintering method exhibit higher translucency than ceramics sintered by the conventional method.^{12,39,62} Additionally, it has been observed that Y-TZP ceramics sintered by field-assisted spark plasma sintering technology exhibit less porosity and smaller particle sizes.³⁹ Yang et al.⁶³ concluded that after rapid sintering, the optical properties of zirconia ceramics, including their translucency and color, changed so little that they were almost imperceptible to the naked eye.

Intrinsic Parameter 9: Cooling Protocols

Y-PSZ systems with a yttria content of 3-7 mol% consist of a T-phase formed by controlled diffusion and a metastable T-phase formed by a diffusion-free transformation from the C-phase by rapid cooling of the material from temperatures above 1425 °C. They have two types of T-phases. The T-phase is triggered by the displacement of oxygen ions in the crystallographic structure utilizing a diffusion-free mechanism; the fact that the crystal structure formed by this phase exhibits a character close to the isotropic structure can decrease the light scattering caused by birefringence, resulting in a boost in the translucency of zirconia.⁷ Kim⁷ found that the rapid cooling strategy increased translucency, although the translucency of 5Y-PSZ did not match that of glass ceramics.

Extrinsic Parameter 1: Thickness

The overall thickness of monolithic Y-TZP ceramics is significant for the amount of light that penetrates the restoration and thus plays a vital role in the translucency, color, and camouflage capability of the restoration.^{5,17,18} In all investigations examining the influence of restoration thickness on the optical characteristics of monolithic Y-TZP ceramics, the thickness reduced the zirconia translucency.¹⁷ When the thickness is reduced, the restoration becomes more translucent and natural, but it is less resistant to fracture. In contrast, increasing the thickness reduces esthetics and translucency while increasing the durability and stress resistance. In clinical settings, the thickness of conventional monolithic zirconia restorations can be appropriate between 0.5 and 0.75 mm; new generation translucent zirconia restorations can display satisfactory mechanical qualities and esthetic performance at 0.5-1.0 mm.⁵ However, to obtain more translucent restorations, care should be taken to make the restorations thinner. Additionally, in the restorations of discolored teeth, a specific thickness balance should be achieved according to the case, taking into account the masking ability of zirconia.¹⁷ Shen et al.⁶⁴ the translucency of the 5Y-TZP and 3Y-TZP decreased significantly with increasing ceramic

thickness, and the superior translucency of the 5Y-TZP disappeared when the material thickness reached 1.5 mm. Zirconia thickness can be minimized in the presence of a suitable dental background color and when a cement color suitable for restoration is applied. However, in the presence of a discolored/metal background and when opaque cements are used, the zirconia thickness should be increased.¹⁸

Extrinsic Parameter 2: Cementation

Resin cements, which exhibit good esthetics, low solubility, high durability, and high mechanical resistance, are the preferred cement type for all-ceramic restorations. The best choice for cementing zirconia restorations is dual-cure resin cement, which has both chemical and light-curing properties.^{5,12} The cement layer, which acts as an intermediate layer in restorations, can optically affect both the restoration and the existing dental background.^{5,18} Cements are classified as colored, bleached, opaque, or transparent according to their optical properties. The background effect becomes critical as cement transparency increases. As the translucency of the ceramic restoration increases, cement shade becomes critical.^{17,18,65} Opaque cement can be a good choice for masking dark/metallic/discolored dental backgrounds; however, the ceramic thickness must be increased to compensate for the cement color. Choosing an appropriate cement color largely eliminates the need to increase the ceramic thickness.^{17,18} The use of appropriately colored cement can help the masking effect of zirconia and contribute to color harmony for more esthetic results.⁶⁵

Extrinsic Parameter 3: Colors of Y-TZP Ceramics and their Coloring Techniques

Achieving color harmony in monolithic Y-TZP restorations with existing adjacent teeth or restorations present in the mouth is the critical step.¹⁷ In an attempt to enhance the color of zirconia, manufacturers have launched zirconia ceramics with multiple translucency levels (high, super, and ultra), pre-colored zirconia ceramics, multi-layer/multi-chromatic zirconia ceramics, and zirconia ceramics externally dyed by immersion in coloring solutions.^{17,18} Pre-colored zirconia ceramics are produced by adding coloring metal oxides to their structures during the fabrication process.¹⁸ Pre-colored translucent zirconia discs offer optimum translucency and color properties matching the "VITA Classical Shade Guide" shades, minimizing the need for external surface coloring.^{5,17,18} On the other hand, the fabrication of highly translucent multi-layer/multi-chromatic zirconia discs that can mimic the different color and translucency gradient between the dentin and enamel layers from incisal to cervical along the tooth crown has greatly improved the optical properties.^{5,17} There are two different techniques in external coloring procedures: dipping un-sintered or pre-sintered zirconia into solutions containing coloring ions or applying colored primers with a brush on sintered zirconia. These solutions have different shades that match the VITA Classical Shade Guide or the VITA 3D Master shades.^{17,18} Since zirconia has a more porous structure before sintering, coloring solutions can be absorbed more easily at this stage; thus, the material can be easily colored, and color stability is achieved with the sintering process. Metal oxides added to the structure of pre-colored zirconia ceramics and the metal oxide concentration, type, application technique, and time in the colored solutions significantly affect the CIE Lab values and translucency of zirconia ceramics.^{18,66} For this reason, the instructions recommended by the manufacturers should be followed carefully and accurately when coloring zirconia. Although some studies have reported that zirconia ceramics are not easily affected

by coloring processes; there are also studies showing that external coloring procedures reduce translucency when colored and uncolored zirconia ceramics with similar particle sizes are compared. To ensure that the coloring process does not affect the translucency and fracture strength of the material, it is recommended that the coloring content of the solution be adjusted, and the dipping time should not exceed 2 minutes.⁵⁴

Extrinsic Parameter 4: Surface Finishing Protocols and Abrasive Strategies

The effects of procedures such as polishing or glazing recommended for final surface treatments before cementation, such as abrasion with rotary tools, by laser irradiation and sandblasting applied to the intaglio surface of the restoration on translucency, are important issues that should be taken into consideration.^{17,18} Although the color difference between polished and glazed zirconia restorations is lower than the perceptibility limit, the restorations show similar surface brightness due to the decrease in the lightness value in both processes.^{18,54} Various studies reported no difference in translucency between polished and unpolished monolithic zirconia surfaces.^{67,68} However, Kim et al.⁶⁷ observed no difference in translucency parameter values between polished and glazed zirconia. McLaren et al.²⁶ highlighted that polished restorations are more effective than glazed restorations because they exhibit a more natural and realistic appearance and that glaze application alone is not sufficient to provide a natural appearance. Lee et al.⁶⁹ Showed that glazing in zirconia restorations resulted in a higher color difference ($\Delta E=3.27$) than polishing ($\Delta E=2.85$). Manziuc et al.⁶ suggested that both the color and translucency of zirconia ceramics changed after the glazing process, but only the color changes were statistically and clinically significant. Another essential consideration when polishing zirconia is the color stability of the restorations over time. Long-term aging in the oral cavity may induce color shifts in zirconia restorations. Glazing treatments applied to the restoration surface might limit aging by protecting the surface integrity of zirconia.^{18,54}

Extrinsic Parameter 5: Low-Temperature Degradation

LTD causes a decrease in the elastic modulus, flexural strength, and fracture strength of the material as a result of saliva/water exposure and low temperatures to which zirconia ceramics are exposed in the oral environment over time. This causes T→M on the zirconia surface and affects the clinical effectiveness of restorations.^{12,17,39} Aging or mechanical stress can cause a T→M in monolithic Y-TZP ceramics.⁷⁰ The change in translucency after aging, as M-crystals cause more light scattering than T- and C-crystals, is associated with the T→M of zirconia.¹⁷ Smaller particle sizes and higher yttrium oxide concentrations have been suggested to delay the onset of LTD. While the small particle size effectively prevents the T→M. Similarly, yttrium (III) ions provide phase stabilization and therefore slow down LTD.¹² Jerman et al.⁴³ Revealed that the translucency of extra translucent and highly translucent zirconia ceramics increased with thermomechanical aging. Shen et al.⁶⁴ Concluded that 5Y-TZP offers higher LTD resistance than 3Y-TZP. Kim and Kim⁷¹ realized that the translucency of Y-TZP and lithium disilicate glass ceramics increased slightly with increasing aging time, as did the phase transformations and surface changes on the surfaces of pre-colored monolithic zirconia ceramics.

Extrinsic Parameter 6: Dental Background

The dental tissues and basic dental materials present in the patient's mouth serve as the dental background and constitute the deepest layer through which light can pass in a restoration. Dental materials must have the ability to imitate the optical behaviors of enamel and dentin tissue in order to optimize esthetics. Otherwise, background color incompatibilities may occur in the restorations, as well as a background effect on the color and translucency of monolithic zirconia restorations.¹⁸ Zirconia ceramics fabricated by increasing yttria content offer improved translucency; however, in the presence of clinical conditions, such as a colored dental background, they can harm esthetic results due to the reflection of the underlying color.¹⁰ It is important to consider the color of the tooth to be restored during the fabrication of full ceramic restorations. In this context, teeth without discoloration can be better restored with zirconia with high translucency; in the presence of dyschromic teeth, more opaque zirconia restorations are needed to mask the dark background.⁵ The fact that the ceramic thickness in implant-supported restorations is significantly higher than that in tooth-supported restorations may influence the material's translucency. The choice of abutment (titanium or zirconia) can also alter the restoration's translucency.¹⁷ For this reason, some researchers advocate zirconia abutments over titanium abutments, especially for implant-supported fixed all-ceramic restorations in the esthetic area.¹⁸ To compensate for the existing background surface; solutions such as using backgrounds close to the targeted restoration color, masking the background with suitable cements, and increasing the zirconia thickness have been suggested.^{18,72,73} However, it is stated that zirconia with high opacity can mask backgrounds such as colored teeth, metal posts, or metal abutments.⁵ On the other hand, monolithic zirconia restorations are generally produced thicker than zirconia frameworks; this reduces the translucency and background effect of monolithic zirconia restorations. Many manufacturers have created zirconia ceramic materials with various degrees of camouflage capabilities on colored backgrounds (light, medium, dark, metal).¹⁸

CONCLUSION

Based on the findings of this review, the following conclusions were drawn: 1) Zirconia provides better mechanical service than other full ceramic restorations because of its transformation-toughening trait; 2) first-generation zirconia has an opaque appearance because of the lack of a glassy matrix. Therefore, it was used as a coping in fixed partial restorations and veneered with feldspathic ceramics (bi-layered manner); 3) The monolithic manner emerged as an alternative to the bi-layered manner. Therefore, a number of monolithic zirconia materials having varied optical and mechanical qualities, as well as changes in their chemistries, particularly stabilizer content, have been developed; 4) Fourth generation offering multilayer/multi-chromatic zirconia blanks is the ultimate option in the dental market; 5) The optical properties of zirconia restorations are influenced by both intrinsic and extrinsic factors; 6) When choosing materials, clinicians should carefully consider both monolithic zirconia options with different chemical contents and factors that affect the optical properties of the restorations.

MAIN POINTS

- Zirconia, a bioinert polymorphic ceramic, has become a popular restorative material owing to its advantageous features.

- 3Y-TZP restorations also exhibit high opacity owing to the lack of a glassy matrix in the crystallographic structure. Therefore, 3Y-TZP was used as a coping material and veneered with feldspathic ceramics (bilayer manner).

- Several catastrophic complications, including cracking, chipping, and delamination, have been reported in the bilayer manner; to circumvent this, monolithic zirconia restorations with a plethora of different generations have been introduced.

Footnotes

Authorship Contributions

Surgical and Medical Practices: D.T., Ö.Ö., Concept: D.T., Ö.Ö., Design: D.T., Ö.Ö., Data Collection and/or Processing: D.T., Ö.Ö., Analysis and/or Interpretation: D.T., Ö.Ö., Literature Search: D.T., Ö.Ö., Writing: D.T., Ö.Ö.

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