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PARTIALLY STABILIZED ZIRCONIA: MECHANICAL AND OPTICAL PROPERTIES AND EFFECT OF CHAIRSIDE ADJUSTMENTS AND FATIGUING

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بسم الله الرحمن الرحيم

“In the name of God, the Most Gracious, the Most Merciful”

To my parents, the reason why I am who I am..
To my beloved family and loved ones..

UNIVERSITY OF TURKU
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ABSTRACT

Monolithic partially stabilized zirconia (PSZ) is commonly used in restorative dentistry for its strength, wear resistance, esthetics, and biocompatibility. However, the effects of thermo-mechanical fatiguing and chairside adjustments on its mechanical and optical properties are still not fully understood.

This in vitro study evaluated how yttria content, material thickness, simulated mastication, and chairside adjustments affect strength, phase transformation, surface roughness, and optical properties of 3Y-PSZ, 4Y-PSZ, and 5Y-PSZ. Disc specimens (0.7 mm and 1.2 mm thick) underwent biaxial fracture testing before and after mastication simulation (1.2 million cycles, 110 N, 5°C–55°C thermal cycling). Adjustments were performed using either coarse diamond burs or a dedicated zirconia adjustment kit. Flexural strength performed according to ISO 6872 standards; X-Ray Diffraction (XRD) and Scanning Electron Microscopy (SEM) assessed phase transformation and fracture pattern. Atomic Force Microscopy (AFM) and spectrophotometry were utilized to evaluate surface roughness, surface gloss, translucency, and contrast ratio.

Lower yttria content and greater material thickness significantly improved fracture resistance. 3Y-PSZ had the highest strength; 5Y-PSZ, the lowest. Thinner specimens (especially 4Y and 5Y) were more prone to fracture under fatiguing. Coarse diamond adjustments reduced flexural strength and increased monoclinic phase content, particularly in 3Y and 4Y groups. Adjustment with coarse bur only led to significant increase in surface roughness. Utilizing the dedicated zirconia adjustment kit caused less surface damage and phase transformation while preserving optical properties

In conclusion, yttria content and adjustment protocols significantly influence zirconia properties. Higher yttria improves translucency but reduces strength. Chairside polishing preserves properties better than coarse grinding. Clinically, proper adjustment techniques are essential to maintain zirconia’s properties.

Keywords: Monolithic zirconia, Yttria content, Fracture load, Flexural strength, Fatigue, Surface roughness, Optical properties, CAD/CAM, Prosthodontics.

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TIIVISTELMÄ

Monoliittinen osittain stabiloitu zirkonia (PSZ) on laajasti käytössä korjaavassa hammashoidossa sen lujuuden, kulutuskestävyyden, esteettisyyden ja bioyhteensopivuuden vuoksi. Kuitenkin lämpö-mekaanisen rasituksen ja kliinisessä työssä tehtävien muokkausten vaikutuksia sen mekaanisiin ja optisiin ominaisuuksiin ei vielä täysin tunneta.
Tässä in vitro -tutkimuksessa selvitettiin, miten yttriumoksidin määrä, materiaalin paksuus, purentarasitus ja kliiniset muokkaukset vaikuttavat 3Y-PSZ:n, 4Y-PSZ:n ja 5Y-PSZ:n lujuuteen, faasimuutoksiin, pinnan karheuteen ja optisiin ominaisuuksiin. Näytekappaleet (paksuus 0,7mm ja 1,2mm) testattiin murtolujuustestillä ennen ja jälkeen simuloitua purentarasitusta (1,2 miljoonaa sykliä, 110 N, lämpötila 5°C–55°C). Muokkaukset tehtiin joko karkeilla timanttiporilla tai kiillotusjärjestelmällä. Taivutuslujuus mitattiin ISO 6872 -standardin mukaisesti; faasimuutokset ja murtopinnat analysoitiin röntgendiffraktiolla (XRD) ja pyyhkäisyelektronimikroskoopilla (SEM). Atomivoimamikroskoopilla (AFM) ja spektrofotometrialla arvioitiin pinnan karheus, kiilto, läpinäkyvyys ja kontrastisuhde.
Pienempi yttriumoksidipitoisuus ja suurempi paksuus paransivat merkittävästi murtolujuutta. 3Y-PSZ oli vahvin, 5Y-PSZ heikoin. Ohuemmat näytteet (erityisesti 4Y ja 5Y) olivat alttiimpia väsymismurtumille. Karkeat timanttimuokkaukset heikensivät taivutuslujuutta ja lisäsivät monokliinisen faasin määrää, erityisesti 3Y- ja 4Y-materiaaleissa. Kiillotus vähensi vaurioita ja faasimuutoksia. Timanttimuokkaukset lisäsivät myös pinnan karheutta ja vähensivät kiiltoa, mutta läpinäkyvyys ja kontrastisuhde säilyivät ennallaan.

Yhteenvetona: yttriumoksidipitoisuus ja muokkausmenetelmät vaikuttavat merkittävästi zirkonian ominaisuuksiin. Suurempi yttriumoksidimäärä parantaa läpinäkyvyyttä mutta heikentää lujuutta. Kiillotus säilyttää materiaalin ominaisuudet paremmin kuin karkea hionta. Kliinisessä työssä oikeat muokkausmenetelmät ovat olennaisia zirkonian eheyden säilyttämiseksi.

Avainsanat: Monoliittinen zirkonia, yttriumoksidipitoisuus, murtokuorma, taivutuslujuus, väsymisrasitus, pinnan karheus, optiset ominaisuudet, CAD/CAM, protetiikka

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Abbreviations

°C	Degree of Celsius
ADia	Adjustment with Coarse Diamond Only
AFM	Atomic Force Microscope
ANOVA	Analysis of Variance
APol	Adjustment with Complete Steps
CIE	International Commission on Illumination
CR	Contrast Ratio
FDP	Fixed Dental Prostheses
FSZ	Fully Stabilized Zirconia
HT	Katana High Translucent
ISO	International Organization for Standardization
LTD	Low Temperature Degradation
MPa	Megapascal
NA	No Adjustment
n	Number of Specimens in group
PSZ	Partially Stabilized Zirconia
RMS	Root Mean Square
SCE	Specular Component Excluded
SCI	Specular Component Included
SD	Standard Deviation
SEM	Scanning Electron Microscope
SG	Surface Gloss
STML	Katana Super Translucent Multi Layered
TP	Translucency Parameter
UTML	Katana Ultra Translucent Multi Layered
XRD	X-ray Diffraction
Y-TZP	Yttria-Stabilized Tetragonal Zirconia Polycrystals
t→m	Tetragonal to Monoclinic Transformation

List of Original Publications

This dissertation is based on the following original publications, which are referred to in the text by their Roman numerals:

I **Abdulmajeed A,** Sulaiman TA, Abdulmajeed A, Bencharit S, Närhi T. Fracture Load of Different Zirconia Types: A Mastication Simulation Study. *Journal of Prosthodontics*. 2020;29(9):787-791. doi:10.1111/jopr.13242

II **Abdulmajeed A,** Sulaiman TA, Abdulmajeed AA, Närhi TO. Strength and phase transformation of different zirconia types after chairside adjustment. *Journal of Prosthetic Dentistry.* 2024;132(2):455-463. doi: 10.1016/j.prosdent.2022.06.015

III **Abdulmajeed A,** Sulaiman TA, Suliman AA, Abdulmajeed AA, Närhi TO. Surface roughness and optical characteristics evaluations after chairside adjustment of different zirconia types. *Journal of Esthetic and Restorative Dentistry.* 2024;36(7):1075-1080. doi:10.1111/jerd.13246

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1 Introduction

Monolithic zirconia has emerged as a premier material in modern dentistry, prized for its exceptional strength, durability, and aesthetic adaptability. Its widespread adoption has reshaped restorative procedures, particularly in fabricating indirect restorations and implant-retained crowns and fixed prostheses, owing to its superior mechanical properties and biocompatibility (Piconi & Maccauro, 1999). Composed of zirconium dioxide (ZrO_2), zirconia is classified as a polycrystalline ceramic, exhibiting remarkable resistance to wear and fracture (Cattani-Lorente et al., 2014). These characteristics enable it to fulfil both functional and aesthetic demands, making it a preferred choice for restorations in both anterior and posterior regions (Miyazaki et al., 2013). Continuous advancements in material processing and stabilization techniques have further enhanced its clinical performance, solidifying its role as a cornerstone in contemporary dental materials (Denry & Kelly, 2008). Zirconia exhibits polymorphism, transitioning through three distinct crystallographic phases depending on temperature (Denry & Kelly, 2008 and Nistor et al., 2019). At ambient conditions up to approximately 1170ºC, zirconia exists in its monoclinic form. Upon heating beyond this threshold, it transforms into a tetragonal phase, which remains stable up to 2370ºC. Further temperature elevation induces a transition into the cubic phase, persisting until the material reaches its melting point. The tetragonal phase can be stabilized at room temperature through the incorporation of yttrium oxide (Y_2O_3) (Yttria), a process that significantly enhances its mechanical properties, which is the most advantageous characteristic of zirconia (Porter & Heuer, 1977). Furthermore, zirconia materials exhibit a distinctive phase transformation from the tetragonal to monoclinic phase when subjected to stress, such as during the formation of a crack. This transformation, referred to as transformation toughening, significantly enhances the material's strength and fracture resistance (Garvie et al., 1975).

Zirconia is classified into three primary categories based on the molar concentration of yttria: 3 mol% yttria-partially stabilized zirconia (3Y-PSZ), 4 mol% yttria-partially stabilized zirconia (4Y-PSZ), and 5 mol% yttria-partially stabilized zirconia (5Y-PSZ) (Burgess, 2018). Among these, 3Y-PSZ exhibits the highest mechanical strength, making it the most robust variant (Sulaiman et al., 2023). However, its inherent opacity limits its application in esthetically demanding regions. Conversely, 5Y-PSZ offers superior translucency, a desirable optical property, though at the expense of reduced mechanical strength. Positioned between these two extremes, 4Y-PSZ represents a balanced alternative, providing an optimal trade-off between strength and translucency. Despite these variations, translucent zirconia remains a viable material for anterior restorations, effectively meeting the minimum mechanical strength requirements while delivering enhanced esthetic outcomes (Sulaiman et al., 2023).

In the oral environment, teeth and dental restorations are exposed to a variety of mechanical, thermal, and chemical stresses. Over time, these factors contribute to the wear and degradation of both natural teeth and restorative materials, ultimately leading to material failure. Ideally, the selection of new restorative materials should be guided by robust clinical evidence. However, the inherent complexity and high costs associated with clinical trials often pose significant challenges (Hickel et al., 2008). As a result, in vitro testing of dental materials serves as a practical and effective alternative for evaluating their properties and predicting their clinical performance (Behr et al., 2000). Such laboratory-based assessments can provide valuable insights that are often translatable to real-world clinical outcomes (Ilie et al., 2017).

The adjustment of indirect restorations prior to final cementation is a routine and essential step in clinical practice. Chairside adjustments are often necessary to achieve precise proximal contacts, optimal contours, and a harmonious occlusal scheme. However, this adjustment process can affect the mechanical and optical properties of zirconia, raising concerns about its long-term performance (Lee et al., 2016; Guess et al., 2010 and Subaşı et al., 2014). Several factors influence the outcomes of zirconia adjustments, including the type of rotary instrument used, the rotational speed, the extent of material removal, and the specific type of zirconia being adjusted (Sandhu et al., 2017). Despite its clinical significance, there is a lack of standardized guidelines on the proper intraoral adjustment techniques for different zirconia materials. As a result, clinicians often rely on subjective approaches, highlighting the need for evidence-based protocols to ensure the preservation of zirconia's integrity and functionality during chairside modifications.

This research project primarily focused on investigating the mechanical and optical properties of various types of monolithic zirconia, with particular attention to how these properties are influenced by thermo-mechanical fatiguing and chairside adjustment procedures.

2 Review of the Literature

2.1. History of zirconia

The timeline concerning zirconia as a substance extends over several decades, covering the transformation it experienced from being mainly applied in industries to a very significant position within modern medicine and dentistry. Zirconia, formally known as zirconium dioxide (ZrO_2), is a white crystalline oxide of zirconium. Zirconium, is a mineral discovered by a German chemist named Martin Heinrich Klaproth back in 1789 (Wertz et al., 2024). The material initially attracted attention because of its excellent thermal and mechanical properties, which subsequently led to its use in high-temperature and high-stress industrial applications, such as aeronautics, heat insulators, knife blades, oxygen sensors, and nuclear reactors (Anusavice, 2013).

Zirconia remained unexplored for medical applications until 1969, when Helmer and Driskell published the first study highlighting its potential as a biomaterial (Helmer & Driskell, 1969). The breakthrough discovery of zirconia’s transformation toughening mechanism in the mid-1970s (Garvie et al., 1975) marked a turning point, leading to its adoption in biomedical fields. By the late 1980s, zirconia was introduced as a femoral head for hip replacements, pioneered by Christel et al. (Christel et al., 1988). Over the following decades, hundreds of thousands of zirconia femoral heads were implanted. However, the early 2000s saw a wave of failures attributed to zirconia’s susceptibility to thermal degradation, or aging. This issue reached a critical point when 400 femoral heads failed within a single year, causing widespread concern among orthopedic surgeons and patients (Chevalier, 2006).

Despite these setbacks, the dental community recognized zirconia’s untapped potential and began extensive research to refine its mechanical and esthetic properties for dental applications. Initially, zirconia was used as a core material in prosthetic dentistry, layered with feldspathic porcelain to achieve both strength and esthetics, making it suitable for single- and multi-unit fixed dental prostheses (FDP). While chipping of the porcelain veneer was a common issue, fractures of the zirconia core were rarely reported (Kelly & Benetti, 2011). This led to the development of monolithic zirconia restorations, which eliminated the need for layering and addressed some of the earlier challenges.

However, the early monolithic material lacked appropriate esthetic properties. This led the scientists to start developing 'next generations' of zirconia materials for achieving a suitable translucency. Research on high-translucency zirconia dating as early as 2010 was yet another milestone for researchers. Altering the yttria content in zirconia with decreasing alumina content showed enhanced optical properties; however, still considerable clinical strength remained (Fischer et al., 2018). Viewed by the newly invented restoratives 4Y-PSZ (partially stabilized zirconia with 4 mol% yttria) and 5Y-PSZ (5 mol% yttria) as an interesting and optimum balance of mechanical strength and aesthetic quality, they lend themselves well to anterior restorations and posterior restorations alike.

2.2. Zirconia applications in dentistry

Zirconia has emerged as a revolutionary material in dentistry, offering a unique combination of strength, durability, and esthetics. Its biocompatibility, mechanical properties, and resistance to wear have made it a popular choice for a wide range of dental applications. From single-tooth restorations to complex multi-unit prostheses, zirconia has transformed restorative and prosthetic dentistry (Denry & Kelly, 2008; Sax et al., 2011 and Nistor et al., 2019). Either in its monolithic nature or as a framework for veneered porcelain, zirconia offers a great restorative option for crown and FDP materials with many years of clinical success (Sailer et al., 2015 and Zarone et al., 2019). Furthermore, zirconia is increasingly being used for full-arch prostheses, including hybrid dentures and implant-supported fixed prostheses. Its high strength and durability make it suitable for long-span restorations, while its esthetic properties ensure a natural appearance (Mijiritsky et al., 2023). Advances in computer-aided design and computer-aided manufacturing (CAD/CAM) technology have further enhanced the precision and fit of zirconia full-arch restorations.

Zirconia is also used for dental implant abutments and frameworks. High fracture toughness and chemical stability provide long-term reliability in support of prosthetic components. Zirconia implant abutments have excellent soft tissue compatibility and, therefore, contribute to better esthetics by minimizing gingival discoloration often seen with metallic abutments (Fischer et al., 2018). In orthodontics, compared with traditional metal brackets, the white, tooth-colored appearance of zirconia brackets is less conspicuous, providing a more aesthetic alternative (Park et al., 2023).

The use of zirconia as endodontic posts inside root-canal-treated teeth reinforces the weakened structure. These posts have excellent durability and biocompatibility, reducing the risk of corrosion and allergic reactions associated with metal posts (Grech & Antunes, 2019). Their tooth-like color also ensures more natural-looking restorations, especially in anterior teeth.

2.3. Zirconia processing

2.3.1. Blank fabrication

Zirconia processing is based on the preparation of blanks, pre-sintered blocks, or discs used in the CAD/CAM system for the fabrication of dental restorations. Blank fabrication is considered a critical step in the fabrication of zirconia. The manufacturing process of blanks begins with the purification of zirconium dioxide originating from a natural mineral called zircon. The purity of the powder is very important as it can affect the grain size and zirconia phase, which ultimately affects the properties of the material (Stoto et al., 1991).

A slurry is then made by mixing the zirconia powder with a certain amount of binder, dispersants, and a few additives. This slurry is then spray-dried to produce granules and is compacted by uniaxial or isostatic pressing at very high pressure (Grech & Antunes, 2019). Such compaction produces “green-stage” blanks, which are somewhat sintered to offer hard enough but yet machinable rigidity for milling (Fischer et al., 2018). During the operation, parameters such as density and microstructure must be monitored stringently since they serve as good indicators of the final product's overall property homogeneity. A very recent trend, however, is the application of novel approaches such as incorporating nano-sized particles in enhancing the mechanical and optical properties of zirconia.

2.3.2. Sintering processing

Sintering is the prime method through which partially dense “green-stage” zirconia is converted into a fully dense form. It consists of at least two heat-activated processes: densification and grain growth. During this process, the blank is exposed to high temperatures within a controlled furnace, usually maintained between 1350°C and 1600°C, with holding times ranging from 2 to 4 hours (Kui et al., 2023). The sintering times and temperatures have a direct impact on zirconia’s grain size, amount of cubic phase, and yttrium distribution that in turn has an effect on zirconia’s mechanical and optical properties (Denry & Kelly, 2014). While the material becomes denser, the size and distribution of the grains control translucency and the scattering of light. Smaller, dispersed grains give better translucency, which is important for acquiring natural-looking restorations. There is generally a trade-off between translucency and strength, since with higher translucency, one often gets lower fracture toughness (Zhang et al., 2018).

Another important consideration during sintering is the shrinkage; zirconia typically undergoes linear shrinkage of about 20–25% (Lin et al., 2021). This shrinkage requires very exact compensation during the CAD/CAM design phase to precisely ensure the fitting of the final restoration.

Current sintering techniques, such as microwave, spark plasma sintering, and rapid sintering, are being developed to reduce the processing times with no compromise on material properties (Liu et al., 2010 and Al-Haj Husain, 2022). It aims to enhance efficiency in dental laboratories while maintaining the high requirements for clinical applications.

2.3.3. Zirconia coloring (staining)

One of the greatest challenges in gaining widespread clinical acceptance of monolithic zirconia is its inherent opacity and whether it can ever truly replicate the natural color and translucency of human teeth. From a ceramic engineering perspective, incorporating coloring oxides into the zirconia powder before pressing is considered ideal. Another approach involves doping the powder with colorants, though the vast range of required shades makes this method complex and costly. An alternative technique involves infusing zirconia with low concentrations of metal salts, a method explored by Suttor et al. (2004). However, issues such as uneven coloration and shallow diffusion depth have been reported as limitations (Oh et al., 2012).

Research investigating the impact of staining zirconia in their green stage—before sintering—has shown that while staining results in slight reductions in strength and microhardness, it can also cause dimensional changes that may affect the final restoration's fit (Hjerppe et al., 2008). Post-sintering painting of the zirconia with coloring agents is another common technique to obtain natural-looking restoration. However, contradictory results were reported in the literature on their longevity and the effect of those techniques on zirconia properties (Shah et el., 2008; Sedda et al., 2015 and Sulaiman et al., 2020).

These coloring methods influence zirconia at the crystallographic and microstructural levels, which may, in turn, alter its mechanical properties. However, limited research exists on how metal salt-based coloring methods impact both the aesthetics and mechanical integrity of zirconia restorations.

2.4. Material properties

2.4.1. Transformation toughening

Zirconia is a polymorphic material that exhibits different crystalline structures depending on temperature. At room temperature, it exists in the monoclinic (m) phase in its pure form. As the temperature increases to 1170°C, it transitions to the tetragonal (t) phase, and at approximately 2370°C, it transforms into the cubic (c) phase, with its melting point exceeding 2716°C (Subbarao, 1981). However, upon cooling, pure zirconia undergoes a phase transformation from tetragonal to monoclinic (t-m), which is accompanied by a volume expansion of about 3%. This expansion can induce internal stresses, leading to cracking and potentially catastrophic failure (Garvie et al., 1975). To address this issue, the addition of oxide stabilizers such as MgO, La_2O_3, and Y_2O_3 was introduced to stabilize the tetragonal and cubic phases of zirconia at room temperature.

Zirconia is usually partially stabilized with 2-5 mol% yttrium oxide in dental applications, producing yttria-stabilized tetragonal zirconia polycrystals (Y-TZP), also known as partially stabilized zirconia (PSZ) in this series of studies. On the other hand, full stabilization is reached with at least 8 mol% yttrium oxide, therefore generating fully stabilized zirconia (FSZ) (Goff et al., 1999). The metastable tetragonal phase, achieved through yttria stabilization, is highly valued for its exceptional toughness. When a crack propagates through the material, tensile stresses at the crack tip trigger the transformation of tetragonal particles to the monoclinic phase. This transformation is accompanied by a volume expansion, generating compressive stresses that counteract the crack tip and inhibit its propagation, thereby enhancing the material's localized fracture toughness. This phenomenon, known as transformation toughening, significantly improves zirconia's flexural and tensile fracture resistance. However, excessive grinding, thermal fluctuations, or mechanical stresses can overwhelm the compressive forces at the crack tip, allowing the crack to propagate and potentially leading to material failure. While transformation toughening initially enhances zirconia's strength, its long-term performance under fatiguing forces and in moist environments remains a subject of debate. Quantitative clinical assessments are needed to provide definitive answers regarding zirconia's durability under such conditions.

2.4.2. Physical properties

Thanks to the transformation toughening mechanism, monolithic zirconia stands out as the strongest and toughest among all dental ceramics available today. In its partially stabilized form, zirconia exhibits a flexural strength ranging from 600 to 1500 MPa (Tinschert et al., 2000; Aboushelib et al., 2008 and Schultheis et al., 2013). Additionally, zirconia demonstrates exceptional fracture toughness, with values ranging from 6.3 to 11.5 MPa·m^{1}/^{2} (Tinschert et al., 2007 and Aboushelib et al., 2008), further solidifying its position as a leading ceramic material in dental applications. Furthermore, zirconia's high Vickers hardness (around 1200-1400) contributes to its wear resistance, though it may cause wear on opposing natural teeth if not properly polished (Kim et al., 2007).

Zirconia's chemical stability is another notable advantage, as it remains highly resistant to solubility in the oral environment (Piconi & Maccauro, 1999). This property is crucial for withstanding the dynamic and often harsh conditions of the oral cavity. Moreover, zirconia is thermally inert, providing effective insulation against temperature changes and protecting the dental pulp from thermal challenges.

The long-term clinical performance of monolithic zirconia restorations remains an area of ongoing investigation. Multiple clinical studies have reported varying clinical outcomes with a survival rate of 95 % and above at 5 years, 94.7% at 7 years and 72.36% 6 at 15 years (Pjetursson et al., 2018; Gardell et al., 2021; Tartaglia et al., 2015 and Khijmatgar et al., 2024). Furthermore, (Näpänkangas et al., 2015) reported 89% survival rate at 6 years for zirconia crowns done in students' clinics. However, there is a lack of clinical studies examining material's durability after chairside adjustment and fatigue.

2.4.3. Fatiguing of zirconia

Zirconia performance in the oral environment is influenced by various factors, one of which is fatigue. Fatigue refers to the progressive and localized structural damage that occurs when a material is subjected to cyclic loading, such as the repetitive forces experienced during mastication. In the oral environment, zirconia restorations are exposed to both mechanical stresses and chemical interactions and thermal changes, which can contribute to fatigue and eventual failure.

Zirconia undergoes low-temperature degradation (LTD) in the presence of moisture, which accelerates the transformation of the tetragonal phase to the monoclinic phase at the surface (Kobayashi et el., 1980). This phase transformation, combined with cyclic stresses, can lead to the formation of microcracks and surface roughening, ultimately compromising the material's structural integrity (Chevalier et al., 2007). The transformation mainly occurs between temperatures of 200-300°C, is enhanced by water, and starts at the surface of the material and propagates from there onward (Chevalier et al., 1999). However, smaller grain size and more yttria content enhance the resistance to LTD.

In vitro studies have demonstrated that zirconia's fatigue strength is significantly lower than its static flexural strength. For example, while zirconia may exhibit a flexural strength of 800–1500 MPa under static conditions, its fatigue strength can drop to as low as 200–400 MPa under cyclic loading (Zhang & Lawn, 2018). This reduction in strength is attributed to the cumulative damage caused by repeated stresses, which can initiate and propagate cracks over time. Additionally, environmental factors such as temperature fluctuations, pH changes, and exposure to saliva can further exacerbate fatigue-related degradation (Kim et al., 2007). Furthermore, Türkaslan et al. (2019) concluded that experimental fatigue loading was found to alter the fracture pattern compared to monotonic loading. Under fatigue conditions, fractures typically originate from weak areas associated with manufacturing-induced flaws.

Clinical studies have also highlighted the impact of surface treatments on zirconia's fatigue resistance. Grinding, polishing, and sandblasting can introduce surface defects that act as stress concentrators, accelerating fatigue failure (Denry & Kelly, 2008). Conversely, proper surface finishing and the application of protective coatings can enhance zirconia's resistance to fatigue and LTD.

Despite these challenges, zirconia remains a highly durable material for dental restorations. Ongoing research aims to optimize its fatigue resistance through advancements in material composition, processing techniques, and surface treatments. However, long-term clinical data are still needed to fully understand the fatigue behaviour of zirconia in the complex oral environment.

2.5. Optical properties of teeth and zirconia

One of the primary challenges in restorative dentistry is achieving restorations that closely resemble the appearance of natural teeth. Thus, understanding the optical properties of both natural teeth and restorative materials is essential for achieving good esthetic outcomes. Key components that define the esthetic appearance of teeth include color, fluorescence, opalescence, and translucency.

Color is a multidimensional characteristic first described by Munsell, who divided it into three independent dimensions: hue, value, and chroma (Kuehni, 2002). The CIE system further categorizes color using three parameters: L* (lightness), a* (redness to greenness), and b* (yellowness to blueness), with the CIE highlighting the importance of understanding the light spectrum, transmission, and human visual perception (Johnston, 2009).

Fluorescence refers to a phenomenon where a material absorbs light at a shorter wavelength and re-emits it at a longer wavelength, making the object appear to emit light (McLaren, 1997). Opalescence, on the other hand, involves the scattering of shorter wavelengths of light, giving the material a bluish appearance under reflected light and a brownish-red hue under transmitted light (McLaren, 1997). Translucency refers to the ability of a material to allow light to pass through, such that the underlying background can be partially seen (Johnston et al., 1995).

The optical behaviour of materials is influenced by several factors, including light refraction, dispersion, transmission, and absorption (Halliday & Resnick, 1993). Refraction refers to the bending of light as it passes through different mediums, while dispersion occurs when light is separated into different wavelengths, creating a spectrum of colors. Light transmission is the portion of light that passes through a material, and absorption involves the retention of light energy within the material.

In dental ceramics, the optical properties, such as absorption, transmission, and reflection, depend on factors such as crystalline content, chemical composition, and particle size. Materials can be classified as transparent (allowing light to pass unaltered), translucent (allowing light to pass but altering its path), or opaque (absorbing or reflecting light without transmission). Translucency is influenced by material thickness, color, and surface texture. Darker shades of restorations tend to absorb more light, thereby increasing opacity, and increased material thickness also contributes to opacity (Ahmed, 2000). Moreover, surface roughness can lead to more diffuse reflection, further increasing opacity (Villarroel et al., 2011).

In research, several devices are used to measure and compare translucency, including spectrophotometers, spectroradiometers, and colorimeters. A spectrophotometer measures the reflected or absorbed light from a sample, using geometries like specular component excluded (SCE) and specular component included (SCI) to estimate surface gloss (Kress-Rogers & Brimelow, 2001). Spectroradiometers measure the spectral energy distribution of light, with results expressed in luminance and illuminance units (Paravina & Powers, 2004). Colorimeters are used to measure the color of various points on an object's surface, helping quantify color differences between samples (Paravina & Powers, 2004). The accuracy and repeatability of these devices are critical. Accuracy is validated by comparing test specimens to reference specimens, while repeatability is assessed by ensuring consistent measurements across repeated trials (Johnston, 2009).

Translucency is often quantified using the translucency parameter (TP) and contrast ratio (CR). TP measures color differences between a specimen over a white and black background, with values above 2 indicating opacity (Chaiyabutr et al., 2011). CR is the ratio of reflectance from a specimen against black and white backgrounds, with a value of 0 representing maximum translucency (Powers, 1978). Translucency perception is subjective and influenced by factors like age, lighting, and visual experience. Studies have shown that a significant portion of participants can visually perceive subtle differences in translucency, even as small as a 0.06 CR change (Liu et al., 2010). Additionally, the edge-loss effect refers to light scattering at the edges of translucent materials without absorption, which can influence translucency measurements, although its impact on zirconia is minimal due to the material's properties (Bolt et al., 1994).

2.5.1. Translucency of tooth

Understanding the optical characteristics of natural teeth is essential for accurate clinical shade matching. Additionally, the esthetic quality of any restorative material is assessed based on its similarity to the appearance of natural tooth structure. When light interacts with a tooth, it can be either transmitted through the tooth; diffusely reflected, where light scatters in various directions due to surface roughness; specularly reflected, meaning light reflects off a smooth surface at a specific angle; or absorbed and dispersed within the tooth's internal structure (Burkinshaw et al., 2004).

Evaluating the translucency of natural teeth can be quite complex. Spectrophotometers and colorimeters, designed for flat surface analysis, face challenges when applied to the irregular and structurally varied tooth surface, leading to significant variations in translucency and color values as documented in previous research (Joiner, 2004).

Dentin is largely responsible for a tooth's color, transmitting approximately 52.6% of light, while enamel acts as a color modifier with a light transmittance rate of 70.1% (Magne, 1996). Studies indicate that enamel, at a thickness of 1 mm, has a translucency parameter (TP) of 18.7 and a contrast ratio (CR) of 0.55. On the other hand, dentin of the same thickness has a TP of 16.4 and a CR of 0.60 (Yu et al., 2009).

2.5.2. Translucency of zirconia

One of the most significant challenges in zirconia restorations, which continues to require improvement, is their optical properties. Manufacturers and researchers have focused extensively on developing zirconia restorations suitable for use in esthetic areas. The inherent opacity of zirconia is attributed to several factors, including its high refractive index (2.1–2.2), relatively large particle size exceeding the incident light wavelength, low absorption coefficient, and significant opacity across both visible and infrared spectra (Pecho et al., 2012).

Proponents of all-ceramic restorations emphasize zirconia's advantage over metal-based restorations due to its naturally white appearance and the absence of a metal collar, which can create a dark line along the gingiva (Christensen, 2007). Zirconia core systems possess a contrast ratio (CR) of 1, indicating complete opacity (Heffernan et al., 2002; Chen et al., 2008 and Baldissara et al., 2010). This characteristic allows zirconia to effectively mask underlying dark abutments; however, it also poses a challenge in achieving natural optical properties when veneered with porcelain. A key optical phenomenon affecting natural dentition, porcelain-fused-to-metal restorations, and zirconia restorations is the 'double-layer effect,' as described by O’Brien. This effect occurs when light transmits through a translucent outer layer (such as enamel or feldspathic porcelain) before being diffusely reflected by an inner dentin layer, opaque core, or other reflective surfaces, ultimately influencing the perceived color of the restoration (O’Brien, 1985).

As previously noted, the frequent chipping of veneering porcelain contributed to the increasing preference for monolithic zirconia restorations, largely due to their superior mechanical properties, biocompatibility, and reduced manufacturing time and cost. However, monolithic zirconia presents notable esthetic challenges, particularly due to its unavoidable opacity.

Sintering temperature plays a critical role in determining zirconia's optical properties. In fact, (Vult von Steyern et al., 2022) reported that a 5% change in sintering temperature can adversely affect zirconia’s optical properties. Higher sintering temperatures result in increased zirconia grain size, which can reduce translucency as larger grains reflect more light (Denry & Kelly, 2014). Conversely, a reduction in grain boundaries enhances translucency (Denry & Kelly, 2014). Various surface treatments such as staining, glazing, and polishing have been suggested to enhance the appearance of monolithic zirconia, though the long-term stability of these modifications remains uncertain.

Increasing the yttria concentration in zirconia enhances its translucency by promoting the formation of the cubic phase, which is isotropic and allows light to pass through more easily. However, mechanical properties of zirconia are affected by the amount of yttria concentration.

Partially stabilized zirconia (PSZ) can be categorized into three types based on the molar percentage of yttrium: 3% yttria-partially stabilized zirconia (3Y-PSZ), 4% yttria-partially stabilized zirconia (4Y-PSZ), and 5% yttria-partially stabilized zirconia (5Y-PSZ) (Burgess, 2018). Among these, 3Y-PSZ is the strongest, although it is very opaque with a translucency parameter of 12-14, which limits its application to non-aesthetic areas (Sulaiman et al., 2015). In contrast, 5Y-PSZ offers superior optical properties with a translucency parameter of 18–25 but at the cost of mechanical strength (Sulaiman et al., 2023). The 4Y-PSZ serves as an intermediate material, balancing both optical and mechanical qualities with a translucency parameter of 15-18 (Zadeh et al., 2018). Therefore, when selecting zirconia materials for dental restorations, it’s essential to balance the desired translucency with the necessary mechanical strength and masking ability to achieve optimal aesthetic and functional outcomes.

Despite the great progress, zirconia still faces challenges in achieving translucency comparable to that of natural teeth. Residual stresses, surface roughness, and impurities in the material can all affect light scattering and transmission (Hjerppe & Özcan, 2023). Moreover, the reduced mechanical properties of high-translucency zirconia require careful case selection and preparation techniques to avoid failure under occlusal forces.

Multi-layered zirconia is a newer development that incorporates layers of varying composition and translucency to take advantage of the best characteristics of the different generations (Kolakarnprasert et al., 2019). The gradient in translucency and color is thus emulated as it naturally occurs in teeth, eliminating any need for additional veneering or staining.

2.6. Strength of zirconia

Zirconia owes its popularity in restorative dentistry to its strength. Its mechanical properties exceed most other ceramics in regard to high flexural strength, compressive strength, and fracture toughness, hence fitting uses clinically even where particularly unfavourable situations arise (Denry & Kelly, 2014; Piconi & Maccauro, 1999). Zirconia's high flexural strength and fracture toughness are due to its crystalline structure and the transformation toughening mechanism. When stress is applied, zirconia's tetragonal phase transforms into a monoclinic phase at the crack tip, absorbing energy and preventing crack propagation (Garvie et al., 1975). This mechanism significantly enhances its resistance to fracture, even under high masticatory forces, making it ideal for durable dental restorations.

Zirconia exhibits outstanding flexural strength, typically ranging between 300 and 1300 MPa depending on yttria concentration (Sulaiman et al., 2023). The strength demonstrated by zirconia greatly exceeds that of other dental ceramics, including lithium disilicate (300–400 MPa) and feldspathic porcelain (100–150 MPa) (Hjerppe & Özcan, 2023). Flexural strength is considered an indicator of the ability of a material to resist deformation under bending forces, an important aspect for dental restorations facing high occlusal loads.

The unique self-healing property makes zirconia different from other brittle materials that generally fail suddenly after the formation of a crack. Having measurements of fracture toughness between 2.2 and 6 MPa·m$^{1/2}$, zirconia outperforms other ceramics significantly, which guarantees its reliability in clinical applications (Denry & Kelly, 2008 and Sulaiman et al., 2023).

As mentioned earlier, different yttria concentrations in zirconia result in different mechanical and optical properties (Zhang and Lawn, 2018 and Sulaiman et al., 2023). 3Y-PSZ zirconia has the highest fracture toughness (3.5–4.5 MPa·m$^{1/2}$) and flexural strength (900–1300 MPa) values and opacity of all types of zirconia. Its opacity and high color value limit the general use to posterior restorations and framework for veneered restorations. 5Y-PSZ zirconia has enhanced translucency but reduced mechanical properties with fracture toughness of 2.2–2.7 MPa·m$^{1/2}$ and flexural strength of 400–600 MPa. The latest 4Y-PSZ zirconia has translucency and mechanical properties in between 3Y-PSZ zirconia and 5Y-PSZ, with fracture toughness of 2.5–3.5 MPa·m$^{1/2}$ and flexural strength of 600–800 MPa.

Sintering is another essential factor affecting zirconia strength. Proper sintering will reduce residual porosity, while optimized grain size will allow high strength to be attained; over-sintering results in excessive grain growth and has a detrimental impact on the transformation toughening effect, affecting its fracture resistance (Grech & Antunes, 2019).

2.7. Fatigue resistance of zirconia

Fatigue resistance refers to a material's ability to resist failure under repeated or fluctuating stresses over time. This translates to the material's ability to withstand masticatory forces encountered during normal chewing and biting activities (Zhang et al., 2013). The cyclic stresses in the oral environment can lead to the propagation of microcracks, potentially resulting in material failure (Borges el al., 2009).

Zirconia is particularly well-regarded for its ability to resist failure under cyclic loading, primarily due to the mechanical properties discussed above. However, like all materials, zirconia's fatigue resistance is influenced by several factors, including material composition (yttria mol%), sintering methods, surface conditions, and applied loading conditions. For instance, surface microcracking increases susceptibility to LTD, which reduces the performance of zirconia significantly (Huang et al., 2003). One study investigated the fatigue behaviour of 3Y-PSZ and identified preexisting processing flaws as the primary source of fracture in all cases, with microcracking being the dominant fatigue damage mechanism (Liu et al., 1991). The LTD-induced phase change from the tetragonal to monoclinic phase, coupled with cyclic stresses, can result in the development of microcracks and surface roughening, thereby compromising the material's structural integrity (Chevalier et al., 2007).

When compared to other common dental materials like porcelain and resin-based composites, zirconia generally exhibits superior fatigue resistance. Porcelain, though aesthetically pleasing, has lower fracture toughness and is subject to catastrophic failure under cyclic loading (Zarone et al., 2019). Resin composites have poor fatigue resistance and degrade with time, especially under the conditions of moisture and thermal cycling in the oral environment (Jitwirachot et al., 2022). Zirconia, with its high fatigue resistance, is ideal for posterior crowns where higher occlusal forces are usually encountered.

Many strategies have been employed with regard to enhancing fatigue resistance for zirconia. Such includes the mechanical modification of surface properties of a restoration to make it enhance its mechanical strength and hence low susceptibility to crack initiation (Lin et al., 2021).

2.8. Surface roughness of finished zirconia

Surface roughness plays a crucial role in the performance and longevity of zirconia restorations. A smooth surface is essential for enhancing the aesthetic appearance, reducing wear on opposing teeth, and minimizing the risk of bacterial accumulation, which can lead to periodontal issues or secondary caries (Shelar et al., 2021). Proper finishing and polishing procedures play a significant role in reducing the surface roughness and should always be carried out in a meticulous way utilizing proper tools (Al Hamad et al., 2019). Rough ceramic surfaces exhibit a greater percentage of live bacteria and biofilm coverage (Abdalla et al., 2020). The roughness of zirconia restorations significantly affects their mechanical properties, including fracture resistance and fatigue strength (Barreto et al., 2023). Furthermore, the rougher surface of zirconia can lead to more wear of the opposing dentition (Janyavula et al., 2013). A smoother surface generally results in better performance by reducing stress concentrations that can initiate crack formation.

Several factors can influence the surface roughness of zirconia, including the manufacturing process, such as milling or sintering, and the types of finishing techniques employed (Khayat el al., 2018). For instance, roughness can be introduced during the milling process, depending on the type of milling machine and the material used for the milling instruments. Additionally, surface treatments like polishing, glazing, and sandblasting can alter the surface texture, with polishing generally producing a smoother finish, while sandblasting may increase roughness by introducing microscopic abrasions (Chong et al., 2015; Park et al., 2017; Zhang et al., 2019 and Yahyazadehfar et al., 2021). Careful control of these factors is essential to achieve optimal surface quality, as rough surfaces can lead to increased wear, reduced strength, and compromised esthetics over time.

2.9. Zirconia chairside adjustments

During delivery appointments, chairside adjustments to zirconia restorations may be necessary. These adjustments are commonly made to the occlusal surfaces to address working or nonworking interferences. Additionally, proximal adjustments may be needed to ensure proper seating when restorations are over-contoured or when proximal contacts are too tight. Aesthetic or functional adjustments may also require modification of the contours. The key for successful adjustment is the sequential use of a diamond bur, which can roughen the ceramic surface, followed by polishing to restore the smooth finish and optimize the restoration's performance and appearance (Irusa et al., 2024). Multiple manufacturers have designed adjustment kits that are mainly diamond burs ranging from coarse to fine grit and abrasive polymeric polishing cups and points. Several in vitro studies have compared the effectiveness of different polishing systems on dental ceramic substrates following simulated chairside adjustments, yielding varying results (Park et al., 2017; Amaya-Pajares et al., 2016 and Steiner et al., 2015). The use of a fine polishing paste after polishing steps involving rubber wheels and points has been shown to significantly reduce surface roughness, achieving results comparable to those of glazed specimens (Mahrous et al. 2022).

Chairside adjustment of zirconia with a diamond bur can lead to a negative effect on the properties of the material. Grinding zirconia with coarse-grit diamonds induces phase transformation (Mohammadi-Bassir et al., 2017). Excessive phase transformation will compromise the strength and fracture toughness of zirconia, as the monoclinic phase is inferior to the tetragonal phase in this respect (Denry and Kelly 2008 and Mahrous et al., 2022). In vitro studies reported a reduction in the flexural strength of zirconia following simulated chair-side adjustments (Michida et al., 2015 and Kosmac et al., 1999). Furthermore, adjustments can lead to perceptible changes in the optical properties of zirconia (Kim et al., 2013; Al-Zordk et al., 2022 and Saker et al., 2021).

3 Aims

The research presented in this thesis is based on the working hypothesis that monolithic zirconia with varying yttria concentrations exhibits acceptable optical and mechanical characteristics to be used as a full-contour restorative material.

Accordingly, the following aims were established to:

1. Compare the biaxial fracture load of zirconia materials with varying yttria concentrations (3Y-PSZ, 4Y-PSZ, and 5Y-PSZ) at different thicknesses and investigate the impact of mastication simulation on the fracture load values of these zirconia variants (Study I).
2. Evaluate the effect of two different chairside adjustments on the mechanical properties of three types of zirconia (3Y-PSZ, 4Y-PSZ, and 5Y-PSZ). (Study II).
3. Evaluate the impact of two different chairside adjustments on the surface roughness and optical properties of three types of zirconia (3Y-PSZ, 4Y-PSZ, and 5Y-PSZ). (Study III).

4 Materials and Methods

4.1. Materials used in the studies

4.1.1. Partially stabilized zirconia

The monolithic zirconia materials that were used in the experimental studies are listed in Table 1. These materials differ in their yttria content.

Table 1. The monolithic zirconia materials used in the experimental studies.

ZIRCONIA TYPE	SHRINKAGE FACTOR	YTTRIA CONCENTRATION (MOL %)	MANUFACTURER	ABBREVIATION
Katana High Translucent (Ht)	1.254	3 mol%	Kuraray Noritake INC, Japan	3Y-PSZ
Katana Super Translucent Multi Layered (STML)	1.225	4 mol%	Kuraray Noritake INC, Japan	4Y-PSZ
KATANA ULTRA TRANSLUCENT MULTI LAYERED (UTML)	1.246	5 mol%	Kuraray Noritake INC, Japan	5Y-PSZ

4.1.2 Adjustment instruments

The rotary instruments, including handpieces and burs, used in our studies are summarized in Table 2. A dedicated zirconia-specific finishing and polishing kit (Dialite ZR; Brasseler USA) was employed for specimen adjustment and polishing procedures. The kit includes a range of diamond rotary instruments and polishing cups designed for zirconia surfaces (Figure 1).

Table 2. Handpieces and burs used in the experimental studies.

INSTRUMENT	**MANUFACTURER**	**ADJUSTMENT BURS**	**POLISHING BURS**
Ca 1.5l electric handpiece	Bien-air, USA	NA	NA
Zirconia adjusting and finishing kit (dialite zr)	Brasseler, USA	Fine football dialite diamond (8369df.31.025 fg) extra-fine football dialite diamond (369def.31.025 fg)	Intraoral green medium cup (w17mzr.ra) Orange fine cup (w17fzr.ra)
Coarse diamond bur	Brasseler, USA	Coarse football shaped diamond (6379.31.023 fg)	No polishing

Figure 1: Bur types used for adjustment of zirconia.

4.2 Methods

4.2.1. Preparation of test specimens

4.2.1.1. Preparation of Disk-Shaped Specimens for Various Measurements (Studies I–III)

A total of 300 disk-shaped specimens with a diameter of 14 mm were prepared from zirconia disks using a precision milling machine (PM7 Milling Machine; Ivoclar AG). Sixty specimen thicknesses were set at 0.7 mm (±0.05 mm), and the remaining 240 specimens were set at 1.2 mm (±0.05 mm) according to ISO Standard 6872 to accommodate different testing requirements (ISO 6872, 1995). The sample size was calculated by using a software program (G*Power v. 3.1.9.3; Heinrich-Heine Universität Düsseldorf). Input values were set as effect size f=0.40, a error probability=0.05, and power (1-b error probability) =0.967. The total sample size was determined to be 300 (n=10/group).

Specimens were designed digitally using Blender 3D (Blender, USA) and milled in the different types of zirconia using the PM7 milling machine (Ivoclar, USA). Post-milling, specimens were sintered following the manufacturer's guidelines specific to each zirconia type. After sintering, specimens were ground to the desired thickness using silicon carbide papers with grit sizes of 380, 600, 800, and 1200 under running water. The final dimensions were verified using precision digital calipers (Digimatic Micrometer; Mitutoyo Corp). Specimens were then ultrasonically cleaned in distilled water for 5 minutes and air-dried for 20 seconds. Specimens were randomly assigned to various groups based on zirconia type, thickness, and surface treatment protocols relevant to each study as shown in Table 3.

Table 3: Groups, number of specimens and thicknesses used for each study.

Study	Number of groups	Number of specimens (n)	Thicknesses (mm)
I	6	n= 120 (2/subgroup)	0.70, 1.20
II	9	n=90	1.20
III	9	n=90	1.20

4.2.2. Sintering conditions (Studies I–III)

All specimens were sintered in a high-temperature furnace according to the manufacturer's recommended schedules for each specific zirconia material (Table 4).

Table 4. Sintering condition for the zirconia materials used in the experimental studies.

Zirconia type	Sintering Temperature	Holding Time at Peak Temperature	Total Sintering Time
3Y-PSZ	1500°C	2 hours	Approximately 7 hours
4Y-PSZ	1550°C	2 hours	Approximately 7 hours
5y-PSZ	1550°C	2 hours	Approximately 7 hours

4.2.3 Specimen fatiguing (Study I)

Specimens designated for fatigue testing were subjected to simulated mastication using a mastication simulator (CS-4; SD Mechatronik, Germany). Specimens were embedded horizontally in acrylic resin (VariDur 200; Buehler) within holders coated with petroleum jelly. A releasing agent (Rubber-Sep; Kerr) was applied to the specimens prior to embedding to facilitate easy removal after testing. The fatigue protocol involved cyclic loading with simultaneous thermal cycling. Specimens were loaded with a force of 110 N using a 4 mm diameter spherical steatite indenter for 1.2 million cycles at a frequency of 1.4 Hz. Thermal cycling between 5°C and 55°C was incorporated with a dwell time of 30 seconds at each temperature to simulate oral conditions.

4.2.4. Biaxial fracture load testing (Study I)

After fatiguing, specimens were tested for fracture load using a universal testing machine (Model 4411; Instron). The test setup adhered to ISO Standard 6872 guidelines (ISO 6872, 1995). Specimens were placed on three symmetrically positioned steel balls (diameter 4.5 ± 2 mm) arranged 120° apart on a support circle with a diameter of 11 ± 1 mm. A piston with a diameter of 1.4 ± 0.2 mm applied load to the center of the specimen's top surface at a crosshead speed of 1 mm/min until fracture occurred. The fracture load was recorded using the machine's software (TestWorks; MTS).

4.2.5. Specimen adjustment (Studies II–III)

Specimens underwent different simulated chairside adjustment according to

- No Adjustment (NA): Specimens remained untreated after sintering.
- Adjustment with complete steps (APol): Surface adjustment was performed using a fine-grit diamond rotary instrument (Dialite 8369DF.31.025 FG; Brasseler USA) at 30,000 rpm for 10 strokes, followed by an extra-fine-grit instrument (Dialite 369DEF.31.025 FG; Brasseler USA) for another 10 strokes. Polishing was completed using medium (Dialite W17MZR.RA; Brasseler USA) and fine polishing cups (Dialite W17fZR.RA; Brasseler USA) at 6,000 rpm until a glossy surface was achieved, typically within 60–80 seconds.
- Adjustment with Coarse Diamond Only (ADia): Surface adjustment was done using a coarse-grit diamond instrument (Dialite 6379.31.023 FG; Brasseler USA) at 200,000 rpm with air-water coolant for 10 strokes. No polishing followed this adjustment.

All surface treatments were performed unidirectionally by a single operator using an electric handpiece (CA 1.5L; Bien-Air) equipped with air-water coolant to mimic clinical conditions.

After surface treatments, specimens were ultrasonically cleaned in distilled water for 5 minutes and air-dried for 20 seconds to remove any residual debris.

4.2.6. Biaxial flexural strength (Study II)

Specimens were subjected to biaxial flexural strength testing following the procedures outlined in ISO Standard 6872. The flexural strength (S) was calculated using the equation: S=−0.2387P(X−Y)d2S=−0.2387Pd2(X−Y)
where:

- SS = biaxial flexural strength (MPa)
- PP = fracture load (N)
- dd = specimen thickness at the fracture origin (mm)
- XX and YY = geometric factors calculated based on the specimen and support dimensions, incorporating Poisson's ratio (ν=0.25ν=0.25 for ceramics)

The values of XX and YY were determined using the following expressions:
X=(1+ν)ln(BC)2+[(1−ν)B22C2]X=(1+ν)ln(CB)2+[(1−ν)2C2B2]

Y=(1+ν)ln(AC)2+[(1−ν)A22C2]Y=(1+ν)ln(CA)2+[(1−ν)2C2A2]
where:

- AA = radius of the support circle (mm)
- BB = radius of the loaded area (mm)
- CC = radius of the specimen disk (mm)

4.2.7. X-Ray diffraction and phase transformation (Study II)

X-ray diffraction (XRD) analysis was conducted to identify and quantify the monoclinic phase in the zirconia specimens. An Empyrean Multipurpose X-ray Diffractometer (Malvern Panalytical) with Cu-Kα radiation (45 kV, 40 mA) was used. Diffraction patterns were collected over a 2θ range from 10° to 90°, with a scan speed of 1°/min and a step size of 0.02°. Data analysis was performed using HighScore Plus software (Malvern Panalytical). The volume fraction of the monoclinic phase (Vm) was calculated using the method described by Toraya et al., (1984):
Vm=1.311×Xm1+0.311×XmVm=1+0.311×Xm1.311×Xm
where:
Xm=Im(−111)+Im(111)Im(−111)+Im(111)+It(101)Xm=Im(−111)+Im(111)+It(101)Im(−111)+Im(111)
ImIm and ItIt represent the intensities of the monoclinic and tetragonal peaks, respectively.

4.2.8. Scanning electron microscopy (Study II)

Specimens were prepared for scanning electron microscopy (SEM) by sputter-coating with gold for 130 seconds at 15 mA to achieve an 80 Å conductive layer. SEM imaging was performed using an S-4700 microscope (Hitachi). Micrographs of the fracture surfaces were taken at a magnification of ×500 to assess surface morphology and fracture characteristics.

4.2.9. Surface roughness measurement (Study III)

Surface roughness was measured using a Dimension Icon Atomic Force Microscope (AFM) (Bruker). A non-contact tapping mode was employed to scan a 10 × 10 μm area on each specimen at a scan rate of 0.996 Hz. The cantilever was set with a 26.1 nm setpoint amplitude and a drive amplitude of 1320 mV. Specimens were cleaned with ethyl alcohol prior to scanning to prevent probe contamination. The root mean square (RMS) surface roughness values were recorded in nanometers. Data visualization and analysis were performed using Gwydion software (Czech Metrology Institute).

4.2.10. Optical properties measurement (Study III)

Optical properties, including surface gloss (SG), translucency parameter (TP), and contrast ratio (CR), were evaluated using a reflection spectrophotometer (CI7600; X-rite).

4.2.10.1. Surface gloss

Surface gloss measurements were determined by calculating the color difference between the Specular Component Excluded (SCE) and Specular Component Included (SCI) geometries. The ΔE*SCE–SCI values were calculated using the CIEDE2000 color difference formula:
ΔE00=(ΔL′kLSL)2+(ΔC′kCSC)2+(ΔH′kHSH)2+RT(ΔC′kCSC)(ΔH′kHSH)ΔE00=(kLSLΔL′)2+(kCSCΔC′)2+(kHSHΔH′)2+RT(kCSCΔC′)(kHSHΔH′)
where ΔL′ΔL′, ΔC′ΔC′, and ΔH′ΔH′ are the differences in lightness, chroma, and hue, respectively, and kLkL, kCkC, and kHkH are weighting factors.

4.2.10.2. Translucency parameter

The translucency parameter (TP) was calculated based on the color difference of each specimen measured over white and black backgrounds:
TP=(LW∗−LB∗)2+(aW∗−aB∗)2+(bW∗−bB∗)2TP=(LW∗−LB∗)2+(aW∗−aB∗)2+(bW∗−bB∗)2
where L∗L∗, a∗a∗, and b∗b∗ are the CIE color coordinates, and subscripts WW and BB denote measurements over white and black backgrounds, respectively.

4.2.10.3. Contrast ratio

Contrast ratio (CR) was determined by calculating the ratio of the spectral reflectance over a black background (YbYb) to that over a white background (YwYw):
CR=YbYwCR=YwYb
A CR value closer to 1 indicates higher opacity, while a value closer to 0 indicates higher translucency.

4.3. Statistical analysis

Statistical analyses were performed using SPSS software (version 26.0; IBM Corp). The normality of data distribution was assessed using the Kolmogorov–Smirnov test. Depending on the variables, one-way or two-way analysis of variance (ANOVA) was conducted to evaluate the effects of zirconia type, specimen thickness, surface treatment protocol, and fatigue cycling on the measured properties. Post hoc multiple comparisons were performed using the Tukey Honestly Significant Difference (HSD) test or the Tukey–Kramer adjustment for pairwise comparisons. A significance level of $\alpha = 0.05$ was set for all statistical tests.

5 Results

5.1. Biaxial fracture load (Study I)

Table 5 summarizes the mean and standard deviation of biaxial fracture load (N) for all tested groups. Yttria concentration and specimen thickness significantly affected the mean fracture load ($P < 0.05$). The fracture load was highest in 3Y-PSZ, followed by 4Y-PSZ and 5Y-PSZ, with significant differences ($P = 0.012$). The 1.2 mm thickness groups showed significantly higher fracture loads than the 0.7 mm groups, regardless of yttria content or test condition (baseline/post mastication) ($P = 0.002$). Mastication simulation did not significantly affect the fracture load of any group ($P = 0.339$). However, 3Y-PSZ and 4Y-PSZ (1.2 mm thickness) survived the simulation without fractures. In the 0.7 mm 4Y-PSZ group, 50% of specimens fractured during the simulation, with fractures occurring at 178,000, 135,000, 800,200, 850,000, and 1,030,000 cycles. In the 0.7 mm 5Y-PSZ group, 70% fractured, with failures at 144,000, 190,000, 168,000, 210,000, 218,000, 716,000, and 780,000 cycles. For 5Y-PSZ at 1.2 mm, only 20% fractured, with failures at 239,000 and 442,000 cycles.

Table 5. Mean and standard deviation (SD) of the biaxial fracture load (N) of all groups.

Zirconia thickness/type	Baseline Biaxial Fracture Load (Mean ±SD)	Post Mastication Simulation Biaxial Fracture Load (Mean ±SD)	Percentage of Fractured Specimens During Mastication Simulation (%)
0.7 mm/3Y-PSZ	538 ± 45	512 ± 42	0%
1.2 mm/3Y-PSZ	1199 ± 113	1155 ± 111.6	0%
0.7 mm/4Y-PSZ	454 ± 39	323 ± 43.8[a]	50%
1.2 mm/4Y-PSZ	690 ± 62.7	665 ± 72.8	0%
0.7 mm/5Y-PSZ	307 ± 31.4	295 ± 39[b]	70%
1.2mm/ 5Y-PSZ	506 ± 46	96 ± 42.6[c]	20%

[a] Based on 5 surviving specimens. [b] Based on 3 surviving specimens.

[c] Based on 8 surviving specimens

5.2. Biaxial flexural strength (Study II)

The mean and standard deviation of biaxial flexural strength (MPa) for all groups are summarized in Table 6. The highest to lowest strengths were observed in 3Y-PSZ, 4Y-PSZ, and 5Y-PSZ, with significant differences (P = 0.007) (Figure 2). Adjustment significantly affected the flexural strength of all zirconia types (P < 0.05). No significant difference was found between the effects of APol and ADia on 3Y-PSZ (P = 0.603), 4Y-PSZ (P = 0.993), or 5Y-PSZ (P = 0.660).

Table 6. Mean and standard deviation of biaxial flexural strength (MPa) of different zirconia types after chairside adjustment.

Zirconia type	**NA**	**APol**	**ADia**
3Y-PSZ	985 ±51^{a}	703 ±38^{b}	667 ±52^{b}
4Y-PSZ	602 ±68^{a}	418 ±18^{b}	422 ±19^{b}
5y-PSZ	377 ±34^{a}	156 ±7^{b}	168 ±7.61^{b}

Different superscripted letters in the same row show significant differences (*P*<.05).

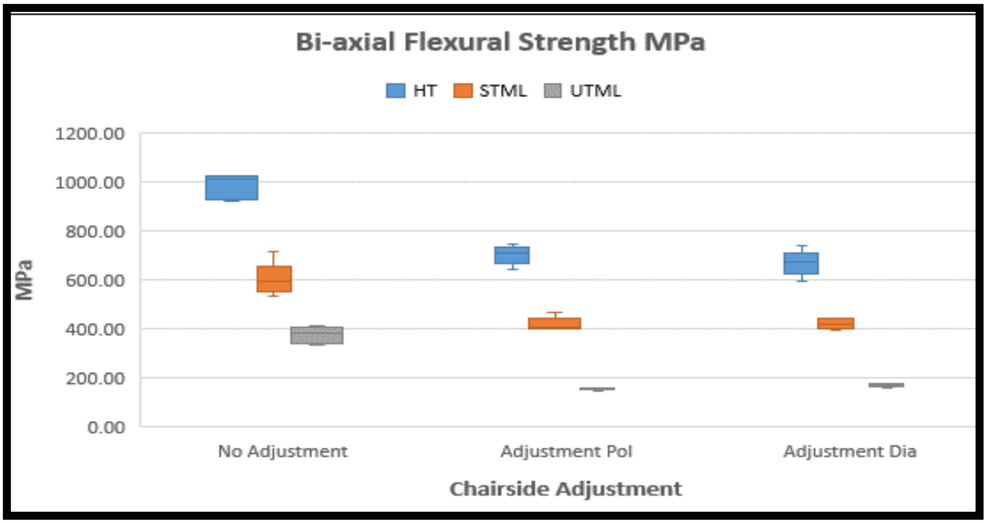


Figure 2. Comparison of biaxial flexural strength of different zirconia types after chairside adjustment. HT, High Translucency Zirconia; STML, Super Translucent Multi Layered Zirconia; UTML, Ultra Translucent Multi Layered Zirconia. No adjustment, specimens untouched; Adjustment Pol, specimens adjusted and polished following protocol; Adjustment Dia, specimens adjusted with coarse diamond rotary instrument with no polishing.

5.3. Phase transformation (Study II)

XRD spectra in Figure 3 show monoclinic phase peaks in 3Y-PSZ and 4Y-PSZ. Table 7 summarizes the volume fraction (Vm) of the monoclinic phase, with ADia groups showing significantly higher values than APol groups, regardless of zirconia type ($P < 0.05$).

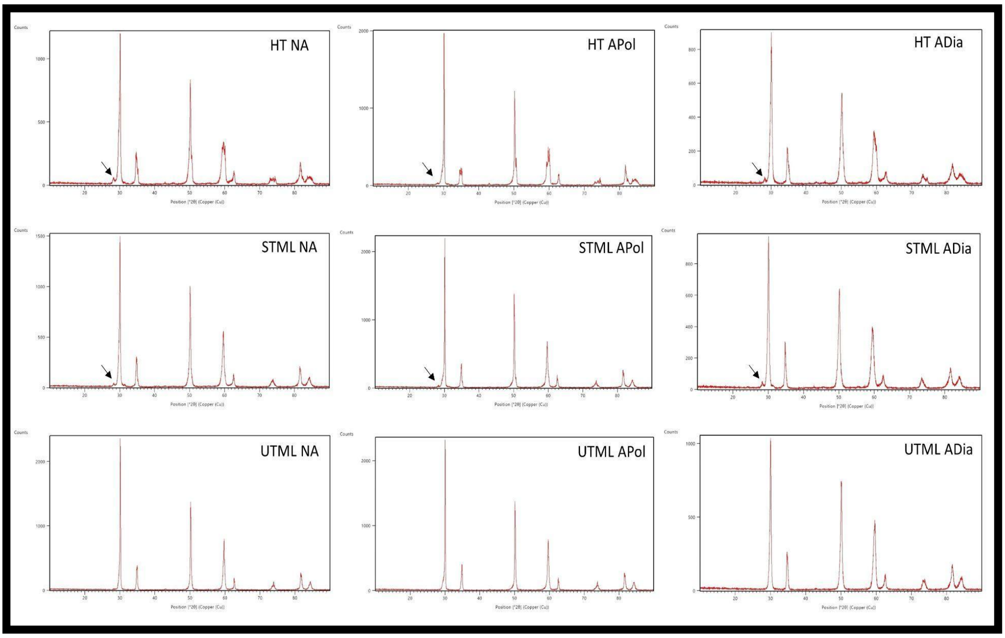


Figure 3. XRD spectra of all tested groups. Arrows indicating monoclinic peaks. NA, No adjustment; ADia, Adjustment Dia; APol, Adjustment Pol; HT, High Translucency Zirconia; STML, Super Translucent Multi Layered Zirconia; UTML, Ultra Translucent Multi Layered Zirconia; XRD, X-ray diffraction.

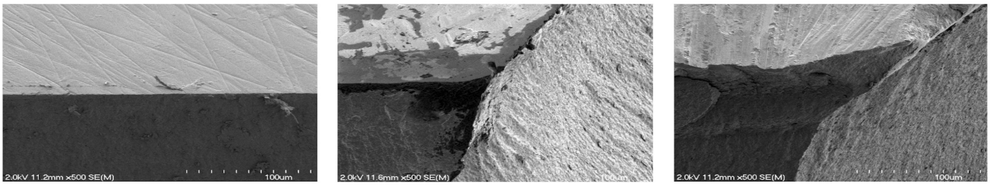
Table 7. Relative Amount (%) of Vm.

Zirconia type	APol	ADia
3Y-PSZ	1.95^{a}	3.6^{b}
4Y-PSZ	1.7^{a}	3.9^{b}
5y-PSZ	-	-

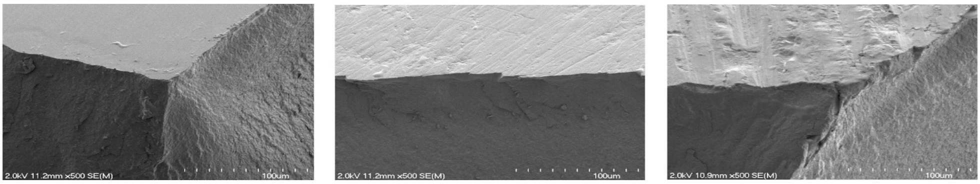
Different superscripted letters in the same row show significant differences ($P<.05$)

5.4. Scanning electron microscopy (Study II)

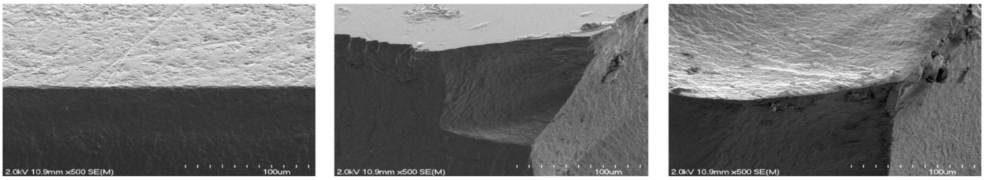
SEM images in Figure 4 show that NA Group specimens had relatively homogeneous fracture surfaces with minimal irregularities, typically resulting in a more uniform fracture line. In contrast, surfaces from both APol and ADia groups displayed more irregular, scattered fracture lines originating from scratches and surface defects induced by the adjustment procedures. The APol surfaces appeared smoother than those adjusted only with the coarse diamond bur.



HT NA HT APol HT ADia



STML NA STML APol STML ADia



UTML NA UTML APol UTML ADia

Figure 4. Representative SEM micrographs (original magnification ×500) of all groups. ADia, Adjustment Dia; APol, Adjustment Pol; HT, High Translucency Zirconia; NA, No adjustment; STML, Super Translucent Multi Layered Zirconia; UTML, Ultra Translucent Multi Layered Zirconia.

5.5. Surface roughness (Study III)

The surface roughness of the specimens varied according to the adjustment method employed (Figure 5). The root mean square (RMS) surface roughness values ranged from 12.5 nm to 378 nm. APol treatment did not produce a statistically significant effect on the surface roughness of the zirconia specimens ($P = 0.88$). However, RMS values were generally higher in the APol groups compared to the non-adjusted groups. On the other hand, ADia significantly influenced the surface roughness of the specimens, irrespective of the type of zirconia used ($P < 0.05$). The mean and standard deviation of the RMS values for all groups are provided in Table 8.

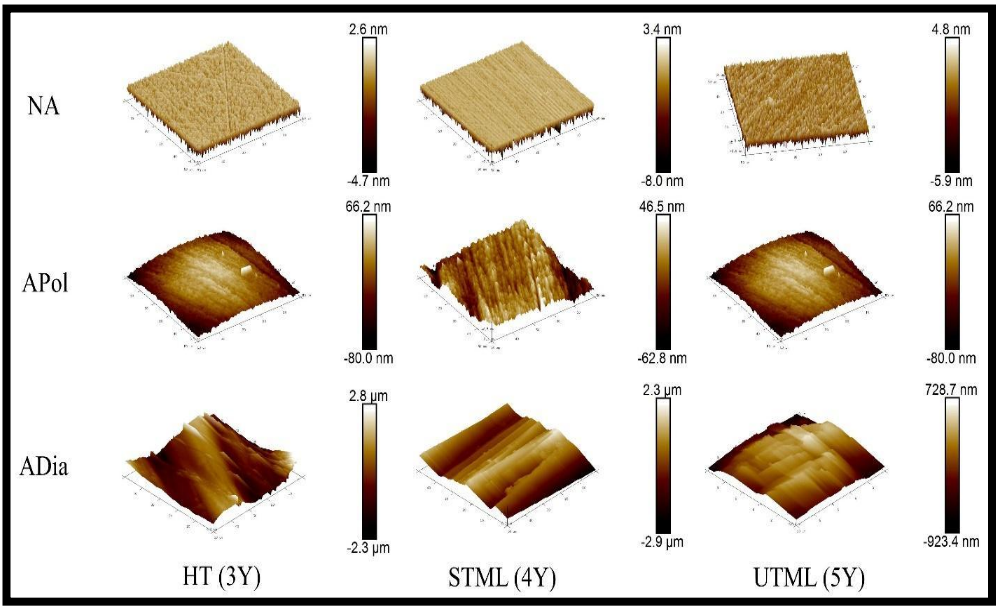


Figure 5. Representative AFM images for each group.

Table 8. Mean and standard deviation (SD) of the root mean square (RMS) of all groups.

Zirconia type	NA	APol	ADia
3Y-PSZ	12.5 ± 0.05^{a}	17.0 ± 6.42^{a}	340.8 ± 32.32^{b}
4Y-PSZ	12.5 ± 0.09^{a}	14.7 ± 1.66^{a}	378.7 ± 43.86^{b}
5y-PSZ	11.4 ± 0.31^{a}	18.8 ± 2.30^{a}	358.1 ± 42.09^{b}

Different superscript letters in the same row show significant differences ($P<.05$).

5.6. Optical properties (Study III)

Mean and standard deviation values of the SG, TP, and CR of different groups according to adjustment method are summarized in Table 9.

5.6.1. Surface gloss

APol treatment had no significant effect on the surface gloss of the zirconia specimens ($P = 0.69$). The surface gloss values for the APol groups were very similar to those of the non-adjusted (NA) groups, with values consistently in the upper 90s across all zirconia types. In contrast, ADia treatment produced a significant negative effect on the surface gloss of all tested zirconia types ($P < 0.05$). The surface gloss values for the ADia-treated groups were notably lower than those of the non-adjusted groups. This reduction in gloss was consistent across all zirconia materials tested

5.6.2. Translucency parameter

The translucency parameter (TP) was not significantly affected by either the APol or ADia protocols ($p = 0.91$). Nonetheless, 5Y-PSZ consistently demonstrated higher TP values than 4Y-PSZ or 3Y-PSZ under any given adjustment condition.

5.6.3. Contrast ratio

No significant changes in contrast ratio (CR) were observed following any of the adjustment protocols ($p = 0.726$). CR values remained stable irrespective of whether specimens were not adjusted, fully adjusted and polished, or subjected to the coarse diamond adjustment alone.

Table 9. Mean and standard deviation (SD) of the surface gloss (SG), translucency parameter (TP), and contrast ratio (CR) of different groups.

Test	**Zirconia type**	**NA**	**APol**	**ADia**
SG	3Y-PSZ	99.5 ± 0.58^a	99.0 ± 1.41^a	21.6 ± 9.68^b
	4Y-PSZ	94.9 ± 2.93^a	97.4 ± 3.99^a	13.9 ± 5.42^b
	5y-PSZ	98.2 ± 1.73^a	99.3 ± 1.53^a	15.7 ± 2.68^b
TP	3Y-PSZ	8.6 ± 0.37^a	8.6 ± 0.93^a	8.5 ± 0.41^a
	4Y-PSZ	9.3 ± 0.92^a	8.7 ± 0.36^a	8.8 ± 0.39^a
	5y-PSZ	12.2 ± 0.53^a	12.1 ± 1.4^a	11.8 ± 1.3^a
CR	3Y-PSZ	0.81 ± 0.01^a	0.78 ± 0.03^a	0.79 ± 0.02^a
	4Y-PSZ	0.71 ± 0.03^a	0.71 ± 0.04^a	0.76 ± 0.01^a
	5y-PSZ	0.63 ± 0.01^a	0.62 ± 0.04^a	0.63 ± 0.04^a

Different superscript letters in the same row show significant differences (P<.05).

6 Discussion

6.1. General discussion

The main aim of this dissertation research was to assess how various monolithic partially stabilized zirconia materials—3Y-PSZ, 4Y-PSZ, and 5Y-PSZ—perform under circumstances simulating actual clinical challenges. Mechanical behavior, phase stability, and surface/optical changes in these zirconias were systematically investigated in three in vitro studies—Study I, II, and III. Under static and simulated mastication loading, Study I investigated the fracture resistance of 3Y-, 4Y-, and 5Y-PSZ at two clinically relevant thicknesses. Building on those findings, Study II examined how a common clinical procedure—chairside occlusal adjustment with rotary instruments—affected the flexural strength and phase composition of the same zirconia types. Study III investigated further the effects of such changes on the surface roughness and optical characteristics—gloss, translucency, and opacity—of the zirconias. These studies taken together give a thorough knowledge of the compromises between translucency and strength among several zirconia generations as well as helpful suggestions for their clinical application. The results are clinically relevant since they guide dentists on how the long-term performance of zirconia restorations may be affected by material selection and clinical changes.

Every investigation was meant to address a particular aspect of zirconia performance. Study I set baseline behavior: it verified that, particularly when used at lower thicknesses, newer, more translucent zirconias (4Y-PSZ and 5Y-PSZ) have lower fracture resistance than traditional 3Y-PSZ. Study II then connected these mechanical results to the material's reaction to grinding changes, therefore showing how induced surface defects and phase changes might affect strength even more. By quantifying how various adjustment/polishing protocols affect the surface smoothness and appearance of each zirconia type, Study III addressed the clinical reality that any change must be followed by polishing. These studies taken together mimic the path of a restoration from fabrication to intraoral service: from first structural integrity (Study I) to changes during placement (Study II and III) and the resulting surface state. Combining the findings will help us make significant clinical recommendations—for example, guaranteeing sufficient coping thickness for high-translucency zirconia (at least 1.0–1.2 mm), minimizing aggressive adjustments, and always polishing modified surfaces. This thesis emphasizes, therefore, that although newer 4Y and 5Y zirconias provide better esthetics, they need meticulous handling and case selection to produce long-lasting results. Emphasizing their clinical relevance and consistency with current research, the following parts cover in depth the mechanical properties, phase transformation behavior, and surface/optical effects observed.

6.2. Mechanical properties (Study I and II)

6.2.1. Yttria content and fracture resistance

The first study revealed a distinct inverse link between yttria concentration and fracture strength of monolithic zirconia. Under same circumstances, 3Y-PSZ always showed the greatest biaxial fracture load or flexural strength, followed by 4Y-PSZ, with 5Y-PSZ displaying the lowest numbers. This pattern persisted in static load testing, after fatigue, and in flexural strength measurements following adjustments. These results correspond with previous studies that showed a decrease in mechanical strength and fracture toughness of zirconia with increasing cubic phase (via greater yttria) (Zhang & Lawn, 2018; Zhang et al., 2016 and Alraheam et al., 2019). Particularly Zhang et al. (2016) measured that conventional 3Y-PSZ is more flexible and tougher than the very translucent 5Y-PSZ, supporting the current findings. Predominantly tetragonal grain structure of 3Y-PSZ drives transformation toughening and greater intrinsic strength, hence improving performance (Denry & Kelly, 2008 and Garvie et al., 1975). By contrast, 5Y-PSZ has a significant cubic phase that achieves translucency; however, cubic grains do not undergo phase transformation, which makes 5Y-PSZ more brittle and susceptible to crack propagation (Zhang et al., 2016; Zhang & Lawn, 2018 and Alraheam et al., 2019). Similar to our findings (Elsayed et al., 2019) concluded that 4Y-PSZ fracture resistance was an intermediate between 3Y-PSZ and 5Y-PSZ in form of crowns bonded to metal abutments. Therefore, regarding mechanical reliability, there is clearly a trade-off: the translucency benefits of newer 4Y/5Y zirconia come at the cost of strength, a reality that must be considered in clinical settings (Stawarczyk et al., 2017 and Burgess, 2018).

6.2.2. Effect of thickness and mastication simulation

Material thickness proved to be a crucial factor in Study I. Specimens 1.2 mm thick had significantly higher fracture loads than those 0.7 mm thick under all conditions. Sorrentino et al., (2016) and Ozer et al., (2018) reported similar results when comparing strength of zirconia as function of material thickness. Clinically, this reinforces long-standing recommendations that adequate core thickness is necessary for zirconia restorations to withstand occlusal forces (Sax et al., 2011). Notably, when a thin, 0.7 mm veneer-like zirconia was subjected to accelerated fatigue in the mastication simulator, a high percentage of 4Y-PSZ and 5Y-PSZ specimens failed during the 1.2 million chewing cycles, whereas 3Y-PSZ of the same thickness survived (Study I). Specifically, only the 3Y-PSZ groups had 100% survival at 0.7 mm, whereas 50% of 4Y-PSZ and 70% of 5Y-PSZ samples of that thickness fractured during the fatigue regimen. These results highlight that high-translucency zirconias are more susceptible to cyclic fatigue damage, likely due to their lower toughness. The absence of transformation toughening in 5Y-PSZ may allow microcracks to grow under repeated loads, culminating in early failures. From a clinical standpoint, this suggests that if 4Y- or 5Y-based restorations are planned in high-stress areas, one should use them at a sufficient thickness (at least about 1.0–1.2 mm) to provide a safety margin (Chen et al., 2024 and Longhini et al., 2019). This minimum thickness recommendation for 4Y/5Y-PSZ is supported by the findings of Study I, and it is consistent with manufacturer guidelines and prior reports that thinner, highly translucent zirconia restorations may not withstand occlusal forces over time. In contrast, 3Y-PSZ demonstrated robust performance even at reduced thickness, owing to its higher fracture toughness and stress-induced strengthening mechanism (Garvie et al., 1975).

6.2.3. Impact of chairside adjustment on strength

Study II showed that any grinding adjustment with a diamond bur causes a notable drop in the biaxial flexural strength of zirconia, regardless of its yttria content. Adjustment introduces surface defects and subsurface microcracks that function as stress concentrators, reducing the effective strength of the material (Kosmač et al., 1999 and Mohammadi-Bassir et al., 2017). Compared to the control (no adjustment) groups, the mean flexural strength of all three zirconia types in our findings decreased significantly after adjustment—either with coarse diamond only or followed by polishing. For instance, 5Y-PSZ disks had an average flexural strength of about 377 MPa with no adjustment, which dropped to about 160–170 MPa following a coarse diamond adjustment—a loss of more than 50%. On adjustment, 4Y-PSZ similarly dropped from about 600 MPa to approximately 420 MPa; 3Y-PSZ (originally highest) also exhibited a notable drop (Study II). These results agree with those of Mohammadi-Bassir et al. (2017), who found that coarse grinding of 3Y-PSZ greatly lowered its flexural strength, and with Kosmač et al. (1999), who showed that aggressive surface treatments can compromise the reliability of Y-PSZ ceramics. The grinding-induced defects being critical sites for crack initiation under load explains most of the strength loss following adjustment. Interestingly, for a certain zirconia type, the fully polished groups (APol) in our study did not demonstrate a statistically greater strength than the unpolished (ADia) groups. Put another way, while polishing eliminated the rough scratches, it did not restore the original strength. This implies either that microcracks caused by first grinding may remain under the polished surface or that the polishing process, although smoothing the surface, cannot reverse the tetragonal-to-monoclinic phase changes and related residual stresses produced by grinding (Guilardi et al., 2017). Guilardi et al. (2017) also discovered that while grinding raised the monoclinic phase fraction in monolithic zirconia, it had no major impact on the biaxial strength of the material, suggesting that transformation toughening may have offset some of the loss of strength in 3Y-PSZ. In the present instance, though, the net impact of grinding was a strength loss across all materials since 4Y- and 5Y-PSZ lack significant phase transformation capacity. The practical message is that any occlusal adjustment to a zirconia crown can weaken it to some extent; hence, clinicians should be aware of this. Whenever feasible, changes should be minor and done with light pressure and water cooling to minimize damage (Karakoca & Yilmaz, 2009). Using a stronger zirconia (3Y-PSZ) or increasing restoration thickness could help to offset catastrophic failure risk if major grinding is expected.

6.2.4. Fracture patterns and failure modes

The fracture behavior seen in both studies offers more understanding of the mechanics. Study II's scanning electron microscopy revealed that samples without modification had fairly smooth, mirror-like fracture surfaces, suggesting that cracks spread from the intrinsic faults at failure in a more controlled way. By comparison, the adjusted groups—particularly the coarse-ground ones—showed more uneven and sharp fracture surfaces with several starting points radiating from grinding flaws and imperfections. Though they showed some scratch lines indicating not all damage was gone, the APol (polished) surfaces looked smoother than ADia. These findings back up the idea that the defects produced by adjustment turned into the new sources for fracture. They also clarify the reasons for the strength decline: a restoration with a damaged surface practically has a lower critical stress for crack propagation. Prior studies (Karakoca & Yilmaz, 2009 and Caglar et al., 2018) that underlined the negative impact of surface defects on ceramic strength have also supported this result in line with the principles of fracture mechanics. From a clinical standpoint, even though a polished zirconia crown will seem smooth to the eye and feel smooth to the touch, one should not forget that its internal strength could still be affected if it underwent severe grinding. Though it was beyond the scope of the current research, it would be appropriate to apply light adjustment methods and think about post-adjustment heat treatment or glaze firing if applicable (Mohammadi-Bassir et al., 2017). Eventually, Studies I and II together show that 5Y-PSZ is the most structurally sensitive, while 3Y-PSZ provides the greatest structural stability in mechanical performance. Dentists need to ensure sufficient restoration thickness and attempt to avoid exposing 5Y-PSZ to significant chairside grinding if they are to effectively utilize its better esthetics.

6.3. Phase transformation (Study II)

Study II's main emphasis was on investigating the tetragonal-to-monoclinic (t→m) phase transformation in zirconia following simulated chairside adjustments. While no phase change was found in the 5Y-PSZ groups, X-ray diffraction (XRD) showed that grinding with a coarse diamond (ADia) caused a detectable (t→m) transformation in the 3Y-PSZ and 4Y-PSZ samples. This is a significant result that impacts the various stabilization degrees of these materials. Under stress or heat produced during grinding, 3Y-PSZ and 4Y-PSZ include a notable fraction of metastable tetragonal grains that can change to monoclinic. In contrast, the 5Y-PSZ is quite stable (about 50% cubic phase or more) and has far fewer tetragonal grains to transform; hence, even strong grinding did not generate a monoclinic XRD signature in 5Y-PSZ (the monoclinic volume fraction remained ~0). Given its high yttria concentration, 5Y-PSZ is not expected to transform (Zhang et al., 2016). The present findings confirm the theory that zirconia's capacity to undergo stress-induced transformation toughening is dictated by the quantity of yttria (and therefore the phase composition). While in 5Y-PSZ that mechanism is mostly dulled (Zhang & Lawn, 2018 and Zhang et al., 2016), lower-yttria zirconia (e.g., 3Y-PSZ) has a reservoir of transformable tetragonal phase that can be activated by the damage of grinding.

Interestingly, the polished groups (APol) in 3Y and 4Y also revealed some monoclinic content, but far less than their ADia equivalents. For instance, 3Y-PSZ disks that were ground and then polished still exhibited a small monoclinic phase fraction (~1.7–1.95%), but the unpolished coarse-ground ones showed roughly double that amount (~3.6%). 4Y-PSZ showed a comparable trend: polished about 1.7% vs unpolished roughly 3.9% monoclinic. Polishing likely removed the outermost layer of severely damaged material, so removing some of the micro-cracked, transformed grains produced by the original grinding. On the other hand, polishing does not entirely undo the phase transformation; once a tetragonal grain has changed to monoclinic (with a 3-4% volume expansion) (Garvie et al., 1975), it stays monoclinic unless a high-temperature reheating (above the reverse transformation temperature) occurs. The current results therefore show that the APol approach, although good for surface smoothness, nonetheless leaves a partially transformed surface. Fortunately, a small rise in monoclinic phase on the surface of 3Y- or 4Y-zirconia is not necessarily bad and could even help to create localized compressive stresses that slow crack propagation (transformation toughening) (Denry & Kelly, 2008). Our findings indicate that although 3Y-PSZ had the greatest monoclinic content following grinding, it also maintained the greatest strength among the materials—implying that the transformation in 3Y-PSZ gave a crack-protective effect to some degree, offsetting the introduced flaws (Guilardi et al., 2017). 5Y-PSZ, on the other hand, cannot depend on such a mechanism; any crack that forms in 5Y will propagate unimpeded by phase change, which accounts for its lower damage tolerance (Zhang et al., 2016).

Reflecting variations in the materials and methods used, the literature shows multiple perspectives on whether phase transformation in zirconia is caused by regular dental bur adjustments. Grinding and air-particle abrasion of conventional 3Y-PSZ did not significantly (t→m) transform, according to Karakoca and Yilmaz (2009). Caglar et al. (2018) also found no observable phase change with several adjustment/polishing techniques. Often using well-sintered 3Y zirconia and maybe less aggressive adjustment settings, these studies could leave the tetragonal phase mostly unaltered. By contrast, Mohammadi-Bassir et al. (2017) found that coarse grinding with a diamond bur did cause phase transformation in 3Y-PSZ, consistent with our results for 3Y-PSZ. Guilardi et al. (2017) conducted another study that revealed grinding followed by hydrothermal aging raised the monoclinic phase fraction at the surface of 3Y zirconia; surprisingly, this did not affect its flexural strength. They suggested that, so long as the damage is superficial, the stress-induced transformation during grinding could even be benign or advantageous in terms of strength. By contrasting several zirconia formulations, the current study adds complexity to these results: although 3Y and 4Y may transform and maybe acquire some toughening, their strength still fell after grinding because of the related microcracks. There was no phase transformation for 5Y; strength was controlled only by the added defects (there was no toughening mechanism to oppose them). Thus, one outcome is that 5Y-PSZ could be more sensitive to grinding damage than 3Y-PSZ since it cannot disperse energy using the t\u2013m transformation (Zhang & Lawn, 2018). This underlines the need for 5Y zirconia's careful handling. Because 5Y has a limited capacity to stop fractures once they start (Zhang et al., 2016), any changes required on a 5Y-PSZ restoration should be as minimal as possible, and the design of the restoration should make up for this by avoiding sharp internal angles or stress concentrators. Conversely, the ability of 3Y-PSZ to change can be viewed as a resilience factor since it offers some "self-healing" via transformation hardening (Garvie et al., 1975). One should not be complacent, however; too much grinding can produce too many flaws and overwhelm even 3Y-PSZ's toughening capacity (Karakoca & Yilmaz, 2009). All things considered; phase analysis of Study II emphasizes that the yttria level of the material essentially changes its reaction to surface damage. When modified, high-translucency cubic-containing zirconias act more like conventional brittle ceramics (e.g., glass-ceramics), while 3Y-PSZ has a particular capacity to prevent crack propagation by means of stress-induced phase change. Still, the safest course of action is to reduce any induced damage, which aligns the advice to improve CAD/CAM processes and restoration fit to lower the need for chairside modifications (Caglar et al., 2018). Doing so helps to preserve the material in its strongest, as-sintered condition and prevents starting the intricate cascade of surface changes and strength loss.

6.4. Effect of chairside adjustment on surface roughness (Study III)

Study III examined zirconia's surface topography following various chairside adjustment procedures. While a complete adjustment and polishing sequence (APol) results in a surface almost as smooth as the original unadjusted condition, the surface roughness findings clearly indicated that an adjustment with only a coarse-grit diamond bur (ADia) creates a very rough surface on any type of zirconia. Reflecting the smoothness of the as-sintered or factory-polished surfaces, the root mean square (RMS) roughness of unadjusted specimens was approximately 11–13 nm for all three zirconia types; these values are very low, on the order of 0.01 µm, suggesting a very glossy surface. Statistically speaking, the APol groups' RMS roughness of about 15–19 nm was not much different from the control ($p = 0.88$). The ADia groups, on the other hand, had RMS values of about 340–380 nm (0.34–0.38 µm), indicating a significant increase in roughness. Coarse grinding caused this to be about 20 to 30 times more surface roughness. The difference between polished and unpolished surfaces was visually clear, as ADia specimens had a matte, gritty texture and APol specimens stayed shiny. These results are logically anticipated; a coarse diamond bur cuts deep grooves into the zirconia surface, while the fine-grit diamond and rubber polishing kit smooth out the scratches. From a clinical perspective, the meaning is clear: after any chairside zirconia modification, polishing is absolutely essential. A zirconia crown left unpolished after adjustment might have negative consequences in many ways. First, rough zirconia is well known to be very abrasive to opposing enamel or restorations; it can accelerate wear of the antagonist tooth surface (Karakoca & Yilmaz, 2009). Increased surface roughness, secondly, can encourage plaque buildup and make the restoration more likely to stain. While the threshold surface roughness for biofilm retention is often cited around 0.2 \u00b5m Ra for dental materials, our unpolished ADia surfaces (~0.35 µm RMS) clearly exceed that, and the polished surfaces (~0.015–0.02 µm RMS) are much lower. Consistent with our findings with RMS measurements, Karakoca and Yilmaz (2009) as well as Caglar et al. (2018) have shown that appropriately polishing zirconia after adjustment can restore the surface roughness to near pre-adjustment levels (usually ~0.1 µm or less in Ra terms). On the other hand, Mohammadi-Bassir et al. (2017) discovered that even after using polishing systems, a higher roughness than the untouched surface could remain, which also corresponds with our minor increase in the APol groups (the APol mean roughness was a few nanometers higher, not statistically significant). Therefore, although polishing might not exactly restore the surface to its original condition, it does bring it into a clinically acceptable range.

One should highlight that the results of the adjustment process in terms of roughness were consistent across several zirconia compositions. Study III found no notable interaction between zirconia type and the impact of the adjustment protocol on roughness; all materials became rough to a similar degree with ADia, and all were smooth with APol (within a few nanometers of each other). When the same tools are used, this suggests that 3Y-, 4Y-, and 5Y-PSZ's grindability and polishability are similar. The small variations in absolute RMS values—for example, 4Y-PSZ ADia was approximately 379 nm vs. 3Y-PSZ ADia approximately 341 nm—were not statistically relevant, so any small difference is probably caused by normal experimental variation. Clinically, this implies that one kind of zirconia is not naturally more difficult than another in terms of the difficulty of attaining a smooth surface following adjustment. Left unpolished, all zirconia grades will have an undesirable rough texture; all can be effectively polished with the right kit to achieve a smoothness on the order of a few nanometers RMS (which corresponds to a mirror-like finish). All materials benefited from the polishing system used in our study—Dialite ZR kit—which confirmed the results of earlier studies indicating that specialized ceramic polishing kits can uniformly lower surface roughness (Caglar et al., 2018). Caglar et al. (2018) tested several polishing systems on monolithic zirconia and discovered that all of them could create smooth surfaces without negative phase changes, therefore supporting that polishing is a safe and useful action.

From a wider perspective, these roughness results connect to the mechanical outcomes mentioned before. A polished surface not only is smoother but also has fewer surface flaws, which could possibly enhance the strength or at least the dependability of the restoration. Although our Study II indicated that polishing did not noticeably raise the flexural strength relative to unpolished (both adjusted groups had comparable strength), polished specimens did have less severe defects, as shown by lower monoclinic content and cleaner fracture patterns. So, polishing probably eliminated the most important defects even if some subsurface damage persisted and the strength did not completely recover. This could imply that polished restorations could have a greater Weibull modulus (reliability) even if the mean strength is comparable—a conjecture in line with certain studies (Kosmač et al., 1999). Polishing does not damage the structure or optical qualities of the material; thus, there is no negative to doing it in any event. Rather than leaving a restoration in the ground state or trying to glaze over a very rough surface, clinicians are strongly urged to polish zirconia following adjustments. While a well-polished zirconia can keep its smoothness long-term, glazing on a rough surface can be unpredictable, and glaze can wear off (Karakoca & Yilmaz, 2009).

All things considered, Study III verified that while chairside adjustment with coarse instruments significantly raises surface roughness, later polishing can efficiently offset this unfavorable impact. The findings support a straightforward clinical rule: "You must polish if you adjust." Following this will help to guarantee the zirconia restoration stays enamel-friendly and plaque-resistant as well as to maintain its strength as much as possible.

6.5. Effect of chairside adjustment on optical properties (Study III)

Apart from mechanical and surface aspects, the third study investigated at how adjustment and polishing influence the optical characteristics of zirconia, specifically surface gloss (SG), translucency parameter (TP), and contrast ratio (CR). The esthetic result of monolithic zirconia restorations depends on these qualities. The results revealed that while surface changes from adjustment have a significant impact on gloss, they have little to no impact on the natural translucency or opacity of the material.

6.5.1. Surface gloss

The gloss of polished surfaces vs unpolished surfaces showed an apparent contrast. Indicative of their smooth, shiny surface, the unadjusted zirconia samples had extremely high gloss values—in the upper 90s gloss units out of 100 for our measurement technique. With values also in the approximately 95–99 range, the APol groups maintained this high gloss; their mean gloss was statistically comparable to the control. This indicates that the polishing technique was able to efficiently restore the reflective surface of the zirconia. Conversely, the ADia groups showed a significant loss of gloss. Coarse grinding by itself brought the gloss levels down to the low tens—an exceptionally matte surface. The difference was clear: ADia samples looked dull and chalky from their rough surface light scattering. All ADia groups showed a statistically notable decrease in gloss compared to their non-adjusted counterparts ($p < 0.05$). These findings are properly in line with the roughness data—a rougher surface reflects light diffusely and therefore looks less glossy. Practically speaking, if a dentist modifies a zirconia crown with a coarse bur and does not polish it, the patient will probably see the restoration looks less shiny or has a different luster relative to adjacent teeth or relative to its original glazed condition. Our findings show, therefore, that polishing can nearly completely restore the gloss. This is consistent with other research indicating that appropriate polishing can reach gloss levels similar to glazed porcelain or original zirconia (Alp et al., 2018). Although we did not specifically compare polishing against reglazing in this work, the high gloss after APol indicates that mechanical polishing by itself may be enough to generate a clinically acceptable gloss on zirconia. Though a smoother surface will usually keep gloss longer than a rough one, gloss is not permanent and can vary with wear over time. The advice is thus once more to polish modified areas to guarantee the esthetics of the restoration (in terms of gloss) are preserved. Our results provide a statistical validation that surface finish mostly determines gloss; roughening may degrade it and re-smoothing the surface can restore it.

6.5.2. Translucency parameter

The translucency parameter is a measure of how much light passes through a material versus being reflected; it’s basically the difference in color of an object over a white and a black background. Study III revealed no statistically significant change in TP for a given material ($p \approx 0.91$) caused by either the APol or the ADia procedures. Alternatively, the material's translucency of 3Y-PSZ, 4Y-PSZ, and 5Y-PSZ was natural and stayed constant whether the surface was ground-made rough or polished. This outcome could first seem unexpected because one could think that a very rough surface (like ADia) would scatter some light and marginally lower translucency. Averaging the light transmission through the bulk of the 1.2 mm thick specimens, though, the TP measurement—taken with an integrating sphere spectrophotometer—shows tthe TP is dominated by the bulk optical characteristics controlled by the composition of the material and grain structure. Especially after the specimen is measured with a backing, a thin disturbed surface layer from grinding probably has little impact on the general light transmission path; any surface scattering is low relative to the total light passing through. TP is not very sensitive to surface polish, another factor being that the material is sufficiently opaque; TP variations would be more noticeable if, say, a surface coating or glaze of varying refractive index was applied, which was not the case here. Our results show that the translucency of partially stabilized zirconia is a natural characteristic not much changed by usual chairside modifications.

Differences in yttria concentration had an impact on TP. Under all circumstances, 5Y-PSZ had the greatest translucency value, as expected, followed by 4Y-PSZ, then 3Y-PSZ. For instance, 5Y-PSZ often had TP values a few units higher than 4Y across our groups, which were then higher than 3Y (this remained true whether the surface was NA, APol, or ADia). This is consistent with reported known translucency ranges in the literature: While 5Y-PSZ may have TP around 18–20 or more, 3Y-PSZ usually has TP around 12–14 for 1 mm thickness (Sulaiman et al., 2015; Zadeh et al., 2018). Our recorded values support the ranges and show that translucency is mostly influenced by the composition of the material (amount of cubic phase) (Denry & Kelly, 2014). Clinically, this means that a dentist does not have to worry that changing a zirconia crown would make it look more opaque or more translucent; those optical qualities are consistent. Regardless of changes, a 5Y-PSZ crown will stay more translucent than a 3Y-PSZ crown. The only warning is that if the adjustment is so aggressive that it significantly thins out a layered structure (not applicable in the monolithic case) or removes a translucent glaze, then the overall translucency of the restoration could change. In our monolithic situation, that was not an issue.

6.5.3. Contrast ratio

Another way to describe opacity is contrast ratio; it measures reflectance over a black versus white background. It is basically the opposite of the translucency parameter; a higher CR indicates an opaquer material. In line with the TP findings, we found no notable variation in contrast ratio caused by the adjustment procedures (no adjustment vs. polished vs. coarse-adjusted). Regardless of surface condition, each material's CR stayed constant; 3Y-PSZ had the highest CR (most opaque), and 5Y-PSZ had the lowest CR (most translucent). This emphasizes once more that the bulk optical property remained constant. For instance, if 3Y-PSZ had a CR around 0.85 initially, it remained approximately 0.85 after grinding or polishing (with slight changes within measurement error). A 5Y-PSZ, on the other hand, could have a CR of about 0.70 and remain at that value following any treatment. These results agree with Zhang and Lawn (2018), who observed that higher cubic phase in zirconia reduces its contrast ratio (increases translucency) and that this is an inherent material characteristic. Any surface roughness added in our study was not sufficient to significantly change CR, probably because CR is assessed under conditions mostly capturing bulk scattering and absorption. Gloss would be much more impacted by a minor surface haze than the total transmitted vs. reflected light in the spectrophotometric measurement.

In practical terms, the lack of impact of changes on TP and CR is encouraging. The dentist's small changes will not much affect the shade and brightness of a zirconia restoration, depending on its translucency/opacity. For example, if a crown was matching the neighboring teeth in translucency before cementation, some refining with a diamond bur may change its appearance to too opaque or too grey. The surface gloss is the only esthetic change to be aware of; as mentioned, polishing should restore it. One subtlety: Surface scattering—like frosted glass—causes an unpolished rough surface to seem a little "whiter" or chalkier to the eye when not backed by anything, even though TP stayed the same. The internal visual effect, however, is controlled by bulk translucency once the crown is cemented into the mouth with a tooth behind it. Polishing removes any seeming color variation brought on by a matte surface, therefore restoring the correct specular reflection and genuine color of the material.

Ultimately, Study III shows that while chairside adjustment has no major effect on the inherent optical properties (translucency, contrast ratio) of zirconia, it significantly affects surface-dependent optical characteristics (gloss). Polishing preserves the gloss completely; the adjustment process keeps the translucency and color neutrality of the material untouched. These outcomes, together with the roughness results, provide a strong case for a standard clinical protocol: carefully modify and always end with polishing to get a smooth, glossy surface. Doing so guarantees the zirconia restoration's strength (as much as possible) and esthetic quality (natural gloss and proper translucency). The three studies taken together offer a 360-degree perspective on how to best use monolithic zirconia: choose the appropriate grade for the situation, guarantee sufficient thickness for strength, reduce major changes, and polish any modified surfaces. Ultimately, following these recommendations will help to maximize the benefits of each kind of zirconia while minimizing their drawbacks, therefore enabling effective and durable restorations.

6.6. Strengths and weaknesses of the study

This thesis presents a series of studies that compare the optical and mechanical properties of monolithic zirconia with varying yttria concentrations. The greatest strength of this study was the inclusion of fatigue testing to investigate the behavior of these materials under simulated mastication. This significantly enhances the clinical relevance of in vitro studies during a period of rapid industrial changes, where clinical trials are scarce for evident reasons. The impact of chairside adjustment on various zirconia types remains inadequately explored and understood in the existing literature. Consequently, it was essential to investigate the impact of different types of chairside adjustment on the mechanical and optical properties to derive evidence-based recommendations that can assist clinicians in executing clinical procedures with precision and enhancing clinical outcomes.

The quest for an ideal in vitro study capable of producing significant clinical insights and recommendations frequently encounters inherent limitations and shortcomings. Only one brand of zirconia was evaluated, and given that pre-sintered zirconia differs in composition and processing among manufacturers, the results may not be entirely applicable to all commercially available materials.

The use of flat, unbonded specimens instead of anatomically shaped crowns bonded to substructures may not accurately reflect clinical scenarios; the objective was to isolate and evaluate the intrinsic mechanical properties of various zirconia types. Bonding to underlying structures may enhance strength, a potential benefit not addressed in this study. Furthermore, mastication simulation cannot fully replicate the intricate nature of intraoral forces and conditions. Studies II and III examined the immediate effects of chairside adjustments, excluding considerations of long-term aging or thermo-mechanical fatigue.

6.7. Prospective of future studies

Monolithic zirconia has emerged as a preferred material among clinicians due to its advantageous properties. Nevertheless, its extensive implementation frequently occurs prior to the existence of substantial scientific and clinical evidence endorsing its long-term efficacy. Monolithic zirconia is recognized for its durability; however, its optical properties are inadequate for accurately replicating natural dentition. Manufacturers have introduced PSZ with varying amounts of yttria to improve translucency. Comprehensive investigations into the microstructure, clinical behavior, and esthetic performance of these newer formulations are essential prior to drawing definitive conclusions or issuing clinical recommendations.

Manufacturers assert that higher yttria zirconia provides improved esthetic outcomes. Numerous in vitro studies have concluded that an increase in yttria content can improve esthetics, albeit at the cost of strength. The clinical benefits of this tradeoff remain unverified, and a balance between strength and esthetics can only be achieved once the perceived optical enhancements are validated perceptually by clinicians and patients alike. Consequently, well-conducted clinical trials are advocated for this purpose.

In vitro studies indicate that the properties of monolithic zirconia may be adversely impacted by various chairside adjustments, particularly regarding surface characteristics. A comprehensive investigation into the extent of this phenomenon and the development of surface topography conducive to positive clinical outcomes would be valuable. Future in vitro and in vivo studies are recommended to investigate the effects of varying yttria content and chairside adjustments on zirconia properties from different manufactures, at different thickness and different testing conditions, which may contribute to the development of clinical guidelines.

7 Conclusions

Based on the findings of the studies included in this thesis, the conclusions can be summarized as follows:

1. The concentration of yttria has a significant impact on the biaxial fracture load of monolithic zirconia. Specifically, 3Y-PSZ exhibits the highest strength, while 5Y-PSZ shows the lowest, with 4Y-PSZ positioned in between these two extremes. Furthermore, a decrease in zirconia thickness adversely affects fracture resistance in all categories. In-vitro mastication simulations demonstrated differing performance contingent on yttria content and thickness, highlighting potential reliability issues of 4Y-PSZ and 5Y-PSZ in specific clinical contexts. Effective communication between clinicians and lab technicians is essential for appropriate material selection and optimal restorative outcomes.
2. Chairside adjustments with diamond instruments can notably compromise zirconia's biaxial flexural strength and induce a tetragonal to monoclinic phase transformation, with the degree of these effects dependent on yttria content. Higher yttria content typically correlates with reduced strength under identical testing conditions. Nevertheless, adhering to an appropriate adjustment and finishing protocol can reduce phase transformation more effectively than relying solely on coarse diamond instruments.
3. Chairside adjustment of zirconia using coarse diamond instruments significantly increases surface roughness and results in a loss of glossiness, thereby impacting its optical properties. When a proper adjustment and finishing protocol is implemented, the resulting surface roughness can match that of unadjusted zirconia while maintaining its optical properties, underscoring the significance of employing refined techniques during clinical adjustments.

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Original Publications

Abdulmajeed A, Sulaiman TA, Abdulmajeed A, Bencharit S, Närhi T. (2020)

Fracture Load of Different Zirconia Types: A Mastication Simulation Study.

Journal of Prosthodontics

I

Abdulmajeed A, Sulaiman TA, Abdulmajeed AA, Närhi TO.
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Journal of Prosthetic Dentistry

II

Abdulmajeed A, Sulaiman TA, Suliman AA, Abdulmajeed AA, Närhi TO.
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Surface roughness and optical characteristics evaluations after chairside adjustment of different zirconia types.
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