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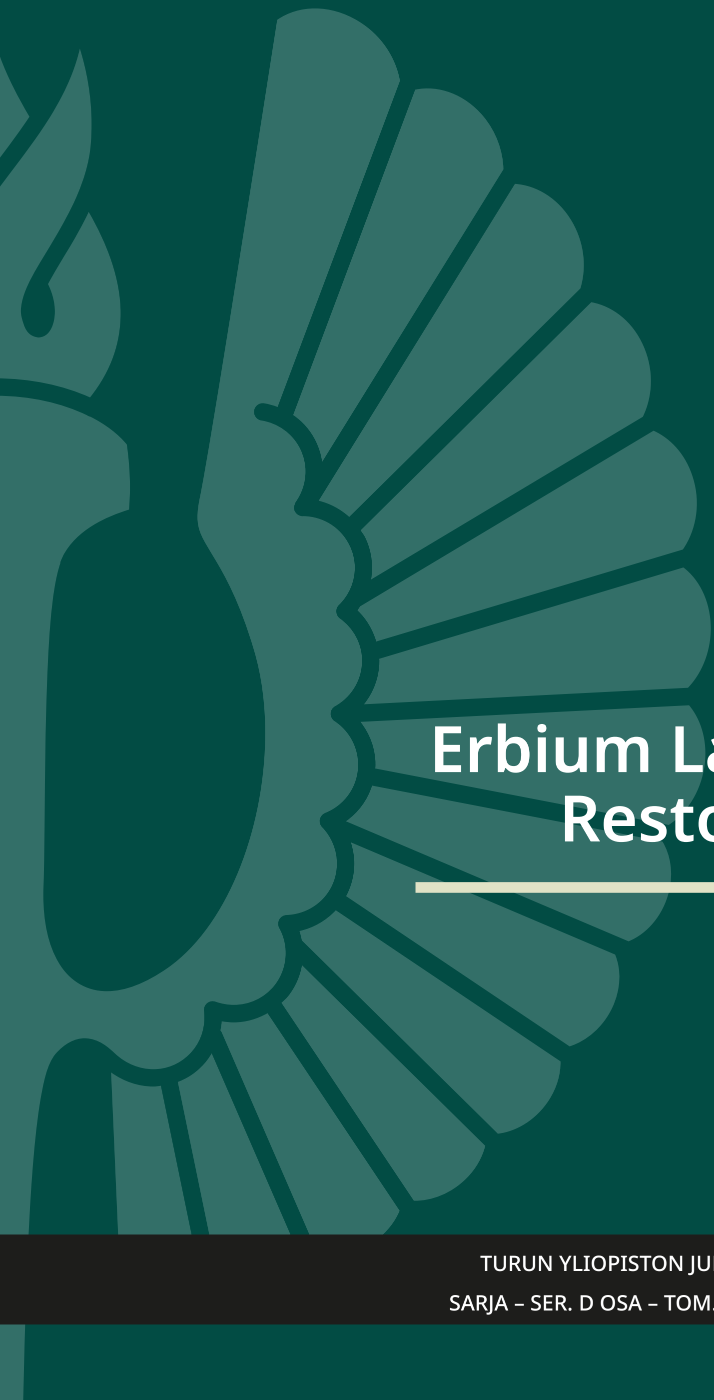

Erbium Laser for Ceramic Restoration Retrieval

Sama A. Suliman

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بسم الله الرحمن الرحيم

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

To my beloved Parents.

UNIVERSITY OF TURKU
Faculty of Medicine
Institute of Dentistry, Department of Prosthetic Dentistry and Stomatognathic Physiology
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ABSTRACT

Conventional removal of all-ceramic dental restorations using rotary instruments can be time-consuming technique-sensitive and may damage both the restoration and underlying tooth or implant abutment. With the increasing clinical use of high-strength ceramics such as yttria-stabilized zirconia (Y-TZP) and lithium disilicate glass ceramics, there is a growing need for non-invasive retrieval techniques that preserve both the restoration and supporting structures. Erbium-doped yttrium aluminum garnet (Er:YAG) lasers have emerged as a potential solution, offering selective cement ablation while minimizing harm to surrounding tissues.

This PhD research aimed to comprehensively evaluate the efficiency and effects of Er:YAG laser-assisted debonding of contemporary ceramic restorations across three experimental studies. The first study investigated the impact of yttria concentration in monolithic zirconia (3Y-TZP, 4Y-TZP, 5Y-TZP) and lithium disilicate on laser debonding time. The second study assessed the influence of adhesive bonding strategy used with resin cements, comparing two-bottle and one-bottle adhesive systems on laser debonding performance. The third study focused on how Er:YAG irradiation affects key optical and mechanical properties of these ceramics, including color stability (ΔE_{00}), translucency parameter (TP), biaxial flexural strength, and surface roughness.

Results demonstrated that debonding time decreased with increased yttria content in zirconia and that lithium disilicate required the shortest retrieval time. No statistically significant differences were observed in debonding time between the two resin cement systems. Er:YAG irradiation caused material-specific changes in color and flexural strength but did not adversely affect surface roughness or translucency in most cases.

In conclusion, Er:YAG laser-assisted removal offers a safe and efficient approach for retrieving ceramic restorations, with minimal alterations to their structural integrity. These findings support the clinical viability of reusing restorations post-debonding and provide a scientific foundation for minimally invasive, laser-guided prosthodontic treatment protocols.

KEYWORDS: Er:YAG laser, yttria content, lithium disilicate, laser debonding, adhesive resin cement, flexural strength, optical properties, surface roughness, CAD/CAM restorations.

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TIIVISTELMÄ

Keraamisten proteettisten rakenteiden poistaminen perinteisesti poraamalla on usein aikaa vievää, teknisesti haastavaa ja saattaa vahingoittaa proteettisen rakenteen lisäksi alla olevaa hammaskudosta tai implanttia. Vahvojen keraamisten materiaalien, kuten yttriumilla stabiloidun zirkonian (Y-TZP) ja litiumdisilikaatilla vahvistetun lasikeramian, yleistyessä on syntynyt tarve kehittää ei-invasiivisia menetelmiä keraamisten rakenteiden irrottamiseksi. Erbium yttrium-alumiini-granaatti (Er:YAG) -laserit ovat osoittautuneet lupaavaksi vaihtoehdoksi, tarjoten selektiivisen sementin irrottamisen samalla minimoiden ympäröivien kudosten vaurioitumisen.

Tässä väitöskirjatyössä arvioitiin Er:YAG-laserin käyttöä nykyaikaisten keraamisten restauraatioiden poistossa kolmen kokeellisen tutkimuksen avulla. Ensimmäisessä tutkimuksessa selvitettiin yttriumin pitoisuuden vaikutusta monoliittisten zirkonia (3Y-TZP, 4Y-TZP, 5Y-TZP) ja litiumdisilikaatilla vahvistettujen lasikeramisten kruunujen irrottamiseen vaadittavaan aikaan. Toinen tutkimus arvioi adhesiivisen sementin tyypin (1- ja 2-komponenttiset järjestelmät) vaikutusta laserkäsittelyllä tehtyyn keraamisen kruunun irrotukseen. Kolmannessa tutkimuksessa selvitettiin Er:YAG-laserkäsittelyn vaikutuksia keraamisten materiaalien optisiin ja mekaanisiin ominaisuuksiin, kuten väristabiilisuuteen (ΔE_{00}), läpikuultavuuteen (TP), biaaksiaaliseen taivutuslujuuteen sekä pinnan karheuteen.

Tulokset osoittivat, että zirkonia kruunun poistoon kulunut aika väheni yttriumin pitoisuuden kasvaessa ja että litiumdisilikaatti kruunu vaati lyhyimmän irrotusajan. Sementtityyppien välillä ei havaittu tilastollisesti merkitsevää eroa kruunujen irrotusajoissa. Er:YAG-käsittely aiheutti materiaalikohtaisia muutoksia väriin ja taivutuslujuuteen, mutta ei vaikuttanut haitallisesti pinnan karheuteen tai materiaalin läpikuultavuuteen.

Johtopäätöksenä voidaan todeta, että Er:YAG-laseravusteinen poisto on turvallinen ja tehokas menetelmä keraamisten restauraatioiden irrottamiseksi, säilyttäen niiden rakenteellinen eheys. Tulokset tukevat restauraatioiden uudelleenkäytön kliinistä toteutettavuutta ja luovat tieteellisen perustan minimaalisen invasiivisille protetiikan hoitomenetelmille.

AVAINSANAT: Er:YAG-laser, yttriumin pitoisuus, litiumdisilikaatti, laserdebondaus, adhesiivinen hartsisementti, taivutuslujuus, optiset ominaisuudet, pinnan karheus, CAD/CAM-restauraatiot.

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Abbreviations

3Y-TZP	3 mol% Yttria-Stabilized Tetragonal Zirconia Polycrystal
4Y-TZP	4 mol% Yttria-Stabilized Tetragonal Zirconia Polycrystal
5Y-TZP	5 mol% Yttria-Stabilized Tetragonal Zirconia Polycrystal
FDP	Fixed Dental Prosthesis
ANOVA	Analysis of Variance
CAD/CAM	Computer-Aided Design / Computer-Aided Manufacturing
CIE	Commission Internationale de l'Éclairage
CVD	Color Vision Deficiency
E.max CAD	Lithium Disilicate Glass-Ceramic CAD/CAM Block
Er:YAG	Erbium-doped Yttrium Aluminum Garnet
FTIR	Fourier Transform Infrared Spectroscopy
Hz	Hertz (frequency; cycles per second)
ICDAS	International Caries Detection and Assessment System
ISO	International Organization for Standardization
L* a* b*	CIELAB Color Coordinates
LED	Light Emitting Diode
$Li_2Si_2O_5$	Lithium Disilicate
nm	Nanometer (one billionths of a meter)
PSZ	Partially Stabilized Zirconia
R_a	Arithmetic Average Roughness
CR	Contrast Ratio
10-MDP	10-Methacryloyloxydecyl Dihydrogen Phosphate
RMGIC	Resin-Modified Glass Ionomer Cement
RMGI	Resin-Modified Glass Ionomer
HEMA	2-Hydroxyethyl Methacrylate
SD	Standard Deviation
SEM	Scanning Electron Microscopy
ΔT	Temperature Change
Er,Cr:YSGG	Erbium, Chromium-Doped Yttrium Scandium Gallium Garnet Laser
QSP	Quantum Square Pulse
SSP	Super Short Pulse

QSP/SSP	Quantum Square Pulse/Super Short Pulse
MSP	Medium Short Pulse
SPSS	Statistical Package for the Social Sciences
mid-IR	Mid-Infrared
FE-SEM	Field Emission Scanning Electron Microscopy
HSD	Honestly Significant Difference (Tukey Test)
TP	Translucency Parameter
UV	Ultraviolet
W	Watt
Y-TZP	Yttria-Stabilized Tetragonal Zirconia Polycrystal
ΔE	Color Difference

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 **Suliman S**, Sulaiman TA, Deeb JG, Abdulmajeed A, Abdulmajeed A, Närhi T. Er:YAG laser debonding of zirconia and lithium disilicate restorations. *Journal of Prosthetic Dentistry*, 2024; 131(2): 253.e1–253.e6. https://doi.org/10.1016/j.prosdent.2023.10.016

II **Suliman S**, Sulaiman T, Deeb JG, Abdulmajeed A, Abdulmajeed A, Närhi T. Effect of Er:YAG laser on debonding zirconia and lithium disilicate crowns bonded with 2- and 1-bottle adhesive resin cements. *Journal of Esthetic and Restorative Dentistry,* 2024; 36(12): 1687–1692. https://doi.org/10.1111/jerd.13274

III **Suliman S**, Deeb JG, Sulaiman T, Abdulmajeed A, Närhi T, Abdulmajeed A. The Effect of Er:YAG Laser Irradiation Debonding Treatment on the Optical and Mechanical Properties of Zirconia and Lithium Disilicate Ceramics. *Journal of esthetic and restorative dentistry: official publication of the American Academy of Esthetic Dentistry, 2025; 37*(12): 2510–2518. https://doi.org/10.1111/jerd.70013

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1 Introduction

Over the past three decades, significant advancements in ceramic materials and adhesive technologies have revolutionized restorative dentistry. These improvements have focused on enhancing both the mechanical and optical properties of dental ceramics to better emulate natural dentition (Deany 1996; Shenoy and Shenoy 2010; Sailer *et al.*2015). Among these materials, lithium disilicate ($Li_2Si_2O_5$) and yttria-stabilized zirconia polycrystals (Y-TZP, $ZrO_2–Y_2O_3$) have gained prominence due to their strength, esthetics, and clinical longevity in diverse restorative indications such as crowns, veneers, inlays, and onlays (Denry and Kelly 2008; Gehrt *et al.*2013; Aziz *et al.*2019). Concurrently, advances in CAD/CAM systems and digital workflows have allowed for streamlined fabrication of these restorations (Guess *et al.*2010; Land and Hopp 2010).

Despite these developments, all-ceramic restorations are still prone to complications and failures over time, whether functional, biological, or esthetic in nature (Zhang *et al.*2018; Rechmann *et al.*2015). Common clinical scenarios that necessitate removal of existing restorations include debonding due to adhesive failure of one of the fixed dental prostheses (FDP) abutments, fracture, secondary caries, endodontic retreatment, or implant maintenance. Conventionally, the retrieval of such restorations is achieved using rotary instruments, which cause irreversible damage to the restoration and/or the underlying tooth structure (Tak *et al.*2015; Gozneli *et al.*2019). Moreover, resin-based adhesive cements with high bond strength further complicate removal due to their strong interaction with both ceramic and tooth substrates (Deeb *et al.*2019; Elkharashi *et al.*2020).

To overcome the limitations of mechanical retrieval, laser-based techniques have been explored as minimally invasive alternatives. A laser (Light Amplification by Stimulated Emission of Radiation) is a device that generates a coherent and highly concentrated beam of light through the process of stimulated emission. Erbium (Er) is a rare earth element belonging to the lanthanide series that is used as an active dopant in solid-state laser crystals. Among these systems, erbium-doped yttrium aluminum garnet (Er:YAG) lasers, operating at a wavelength of 2940 nm, have emerged as promising alternatives for the non-invasive removal of ceramic restorations. The mechanism of action involves the transmission of laser energy through ceramic materials, followed by absorption by water and residual monomers in the underlying luting cement, leading to micro-explosions and thermal ablation (Deeb *et al.*2019; Morford *et al.*2011). The Er:YAG laser has a high affinity for water, enabling it to selectively degrade the cement without affecting the ceramic or tooth structure (Coluzzi *et al.*2010; Rechmann *et al.*2015). This mechanism has shown success in debonding various ceramic restorations, including lithium disilicate, feldspathic porcelain, and monolithic zirconia (Grzech-Leśniak *et al.*2020; Ahrari *et al.*2014).

Initial reports on laser-assisted debonding focused on orthodontic brackets (Dostalova *et al.*2016; Naseri *et al.*2020), but its application has now expanded into prosthodontics. Studies by Deeb *et al.*(2019), Elkharashi *et al.*(2020), and Zhang Y *et al.*(2018) have validated the clinical viability of laser-assisted debonding of ceramic crowns, demonstrating minimal damage to restorations and underlying substrates. However, most of these studies have primarily focused on the efficacy of debonding, with limited investigations into the potential consequences on the ceramic materials' mechanical strength, surface roughness, translucency, or color stability (Zhang *et al.*2021; Kurtulmus-Yilmaz *et al.*2019).

This is particularly critical for zirconia ceramics (ZrO_2), where differences in yttria yttria (Y_2O_3) content (3Y-PSZ, 4Y-PSZ, 5Y-PSZ) result in distinct optical and mechanical properties (Sulaiman *et al.*2015; Zhang 2014; Lim *et al.*2022). While higher yttria content increases translucency and light transmission, it compromises flexural strength (Johnston *et al.*1995; Liu *et al.*2010). These intrinsic differences may influence the efficiency and safety of laser-assisted removal, as well as the clinical viability of reusing the retrieved restoration. Given the increasing interest in cost-effective and conservative dentistry, the potential to reuse debonded restorations, particularly zirconia or lithium disilicate, has garnered considerable attention (Grzech-Leśniak *et al.*2020; Deeb *et al.*2022).

Furthermore, the influence of different adhesive resin cement systems, particularly 1-bottle versus 2-bottle cements, on laser debonding efficacy has not been fully elucidated. In 1-bottle systems, the primer and adhesive are combined in a single bottle, whereas in 2-bottle systems the primer and adhesive are applied separately. These cements vary in viscosity, water content, and polymerization behavior, all of which may affect laser absorption and, consequently, the time required for debonding (Tak *et al.*2015; Gozneli *et al.*2019).

Thus, the aim of this PhD research project was to comprehensively assess Er:YAG laser-assisted debonding in the context of contemporary ceramic materials and resin cement systems. Through a series of three *in vitro* studies, this thesis investigates (1) the effect of different yttria content in zirconia on laser-assisted retrieval times and potential for safe retrieval; (2) the comparative behavior of different adhesive resin cements during laser removal; and (3) the impact of clinically relevant laser parameters on the optical and mechanical properties of ceramics after laser irradiation.

This research provides clinically significant insights into optimizing laser-assisted retrieval protocols and ensuring minimal alteration to the integrity of ceramic restorations. Ultimately, a better understanding of these interactions may support the development of minimally invasive, time-efficient techniques for managing failed or temporarily removed restorations without compromising esthetics or structural performance.

2 Review of the Literature

2.1 Ceramic Materials in Dentistry

In the past decade, there has been a growing demand for metal-free restorations, such as ceramics and resin composites, as replacements for full cast gold or metal-based restorations (Schärer, 1997). This transition is primarily driven by several factors such as cost, esthetics, strength, and biocompatibility of ceramic materials. Ceramic materials offer superior optical properties that closely mimic natural tooth structure and provide excellent corrosion resistance compared with metal alloys. In addition, the growing demand for metal-free restorations and the risk of metal hypersensitivity in some patients have further encouraged their use. Advances in adhesive dentistry and CAD/CAM technologies have also facilitated the fabrication and clinical application of high-strength ceramic restorations (Deany, 1996).

Earlier generations of high-strength all-ceramic systems included alumina (Al_2O_3)-based ceramics, such as In-Ceram Alumina, which were developed to improve the mechanical properties of conventional porcelains. Although these materials demonstrated higher strength than feldspathic ceramics, they were later largely replaced by zirconia-based systems due to the superior fracture toughness and mechanical performance of zirconia (Deany, 1996; Kelly, 2008).

Among the most commonly used ceramics in clinical practice are zirconia and lithium disilicate reinforced glass ceramics, both of which possess distinct properties that make them suitable for a wide range of dental applications, particularly crowns, fixed partial dentures (FPD), inlays, onlays and veneers. From the perspective of cementation, lithium disilicate and other glass ceramics are generally easier to bond than zirconia because they contain a silica-based glass phase that can be etched with hydrofluoric acid and silanized to achieve strong micromechanical and chemical adhesion. In contrast, zirconia is a polycrystalline ceramic that lacks a glassy phase and therefore cannot be etched with hydrofluoric acid; durable bonding relies mainly on air-abrasion surface treatment and functional phosphate monomers such as 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), which can chemically bond to zirconium oxide surfaces and improve the durability of adhesion.

Most all-ceramic crowns are now fabricated using computer-aided design/computer-assisted manufacturing (CAD/CAM) technology, which provides improved control over both production time and cost (Kelly, 2008). In general, the cost of ceramic restorations may vary depending on the material type and fabrication technique. Zirconia restorations are often considered cost-effective due to efficient CAD/CAM milling and simplified fabrication processes, whereas glass-ceramic restorations such as lithium disilicate may involve additional laboratory procedures, which can influence the overall treatment cost. Furthermore, there have been tremendous improvements in the mechanical and optical properties of contemporary dental ceramics. The ability to adhesively bond these restorations to natural teeth or implant abutments is of significant clinical importance. These, together with the growing demands of patients for enhanced esthetics, have increased the use of all-ceramic restorations in dentistry.

Understanding the mechanical and optical properties of dental materials is important to fulfill clinical demands and to ensure satisfactory performance for restoring damaged and/or missing teeth (Kelly and Benetti, 2011; Deany, 1996; Shenoy, 2010; Sailer *et al.*2015; Sari *et al.*2014).

2.2 Zirconia in Dentistry

2.2.1 Properties of Zirconia

Early in the 1990s, zirconia ceramics were first utilized in dentistry. The use of zirconia has rapidly increased in many dental applications due to its excellent mechanical properties, esthetic outcomes, and biocompatibility. The introduction of CAD/CAM technology, combined with these distinctive characteristics, has established yttria-stabilized tetragonal zirconia polycrystals (Y-TZP) as one of the most prominent polycrystalline ceramics in contemporary dental practice (Kelly & Benetti, 2011). Zirconia is predominantly utilized in the fabrication of tooth or implant retained crowns, FPDs, and implant abutments and has been widely adopted for both anterior and posterior restorations.

Zirconia is organized in three different patterns: monoclinic (M), tetragonal (T), and cubic (C). Pure zirconia is monoclinic at room temperature and remains stable up to 1170°C. Above this temperature, it transforms into a tetragonal and then into a cubic phase that exists up to the melting point at 2370°C. During cooling, the tetragonal phase transforms back to monoclinic in a temperature ranging from 100°C to 1070°C (Piconi & Maccauro 1999).

The first generation of zirconia ceramics comprised 3 mol% yttria and 0.25 wt% alumina (Al_2O_3), commonly known as 3Y-zirconia. This generation demonstrated significant strength and low translucency. Improvements to the restoration's translucency were essential for acceptance, considering its cost-effectiveness (Tong *et al.*2016, Sulaiman *et al.*2015, Zhang, 2014). The alumina content was reduced from 0.25 to 0.05 wt%. This led to a reduced concentration of alumina particles at the tetragonal grain boundaries, thereby enhancing light transmission relative to the first generation. The second generation consists of more than 70% tetragonal and less than 30% cubic phases, depending on the sintering temperature, and is typically referred to as 3Y-zirconia (Lim *et al.*2022). It demonstrates significant strength due to a phenomenon referred to as transformation toughening. This indicates that the onset of crack propagation causes the neighboring tetragonal particles to partially transform into the monoclinic phase. Monoclinic crystals demonstrate larger size and volume than tetragonal crystals, leading to a compressive stress surrounding the crack that prevents its propagation. The increasing use of single solid block of monolithic zirconia for fabrication of full contour restorations has prompted manufacturers to investigate techniques to improve the translucency of zirconia, facilitating its application in anterior teeth for cases that demand elevated esthetic standards. Raising the yttria concentration from 3 to 5 mol% improved the translucency of zirconia. The third (5Y) generation zirconia restoration is identified as cubic or translucent zirconia (Garvie *et al.*1975; Hannink *et al.*2000). In general, as the percentage of yttria increases, the translucency increases, and the strength decreases, which leads to premature failure of zirconia restorations. This issue was recognized by manufacturers, and 4Y-zirconia was introduced to increase the strength while keeping an acceptable level of translucency in comparison to 3Y-zirconia. With 60-75% tetragonal or 25-40% cubic content, 4Y-zirconia is known as a zirconia type that can combine strength and translucency (Lim *et al.*2022).

Zirconia is known for its exceptional mechanical strength, with flexural strengths ranging from 800 to 1500 MPa (Tinschert *et al.*2000; Aboushelib *et al.*2008), primarily due to the transformation toughening phenomenon. In comparison, the flexural strength of cortical bone in the maxilla and mandible is considerably lower, typically ranging between approximately 100 and 200 MPa, highlighting the significantly higher mechanical strength of zirconia ceramics relative to natural bone (Kelly & Benetti, 2011). This phenomenon refers to the enhancement of material strength and fracture resistance resulting from the phase transformation of zirconia from the tetragonal to monoclinic phase under applied stress. When zirconia is subjected to stress, the tetragonal phase partially transforms into the monoclinic phase, a process that induces volumetric expansion. This expansion generates compressive stress that impedes crack propagation, thereby increasing the material's toughness. This mechanism is particularly significant in zirconia ceramics, where resistance to crack propagation and the enhancement of mechanical properties are vital, especially in dental applications.

The transformation toughening mechanism is most pronounced in yttria-stabilized zirconia, such as Y-TZP (yttria-stabilized tetragonal zirconia polycrystals), which retains its tetragonal phase at room temperature, contributing to its improved mechanical performance through this unique transformation behavior (Kelly & Benetti, 2011). Despite these favorable mechanical properties, zirconia ceramics may be susceptible to low-temperature degradation (LTD), also referred to as hydrothermal aging. This phenomenon involves the gradual transformation of the tetragonal phase to the monoclinic phase in the presence of moisture at relatively low temperatures, which may lead to surface roughening, microcracking, and deterioration of mechanical properties over time (Piconi & Maccauro, 1999; Denry & Kelly, 2014).

According to literature, conventional 3 mol% yttria-stabilized tetragonal zirconia polycrystal (3Y-TZP) has been reported with high fracture toughness ranging from 2.4 to 6 $MPa \cdot m^{1/2}$. The hardness of zirconia is approximately 14 GPa and the elastic modulus is about 210 GPa (Tinschert *et al.*2007; Aboushelib *et al.*2008; Zhang & Lawn, 2018). Furthermore, zirconia has exceptional chemical stability (Piconi & Maccauro, 1999), which is essential for enduring the oral cavity's fluctuating environmental conditions including changes in temperature, saliva exposure, pH variations, and mechanical stresses generated during mastication. Zirconia is also known for its low thermal conductivity, which protects the pulp from fluctuations in oral temperature. The *in vitro* mechanical properties of zirconia, as documented in the literature, are typically remarkable for a dental ceramic, although definitive outcomes from long term clinical studies are yet to be provided.

Optical properties of zirconia have been noticed as one of the most important factors to consider and many researchers and manufacturers have focused on producing zirconia restorations that can be successfully used in esthetic zones. One of the important optical characteristics of zirconia is translucency, influencing how well light passes through the material and interacts with the underlying tooth structure. Thickness is one of the crucial factors to consider when reviewing the literature to determine the translucencies of ceramic systems. Different thicknesses are needed within a restoration depending on anatomy and preparation, and it is well known that some restorative materials become less translucent as their thickness increases simply because it is difficult for light to pass through thick material (Pecho *et al.*2012; Denry & Kelly, 2014). Zirconia, in its natural state, exhibits comparatively poor translucency, hence restricting its capacity to replicate the esthetic characteristics of natural teeth. Modifications in zirconia compositions have been implemented, primarily through the adjustment of yttria content. Moreover, alterations in the zirconia grain sizes, along with staining, glazing, and polishing zirconia surfaces, have all been advocated to enhance the optical properties of zirconia. Zirconia restorations can be stained either by applying coloring liquids to the pre-sintered zirconia framework before sintering or by using external stains and glazing techniques after sintering to achieve the desired shade and esthetic appearance (Denry & Kelly, 2014). Translucency values are identified as either translucency parameter (TP) or contrast ratio (CR). TP is defined as the color difference between a uniform thickness of a specimen over a white and black background and is considered as a commonly used visual assessment for translucency (Johnston *et al.*1995). A black background can be blocked by TP values of 2 or less (Chaiyabutr *et al.*2011), and as the TP value increases, translucency also increases.

While CR is defined as the ratio of the reflectance of a specimen over a black background to that over a white background of a known reflectance (Miyagawa *et al.*1981). The CR value of 0 is known as the most translucent, while the CR of 1 is the opaquest (Powers *et al.*1978).

In the literature, it is reported that at 1 mm thickness of zirconia, the translucency parameter values can vary between 12 (3Y-zirconia) and 25 (5Y-zirconia); the lower the number, the less translucency there is (Sulaiman *et al.*2015; Zhang, 2014; Lim *et al.*2022). A totally opaque state is also represented by a contrast ratio value of 1. According to reports, the contrast ratio value at 1 mm for 3Y-zirconia is approximately 0.90, while for 5Y-zirconia it is approximately 0.70 (Zhang, 2014; Sulaiman *et al.*2015; Lim *et al.*2022). From a therapeutic perspective, it is essential to comprehend how the eyes perceive translucency. The human eye can perceive the difference in translucency between 3Y- and 5Y-zirconia, with the latter being more translucent, because these reported values are higher than the translucency threshold. Therefore, it is very important to understand all these properties when deciding which type of zirconia is to be used in the clinic.

2.2.2 Clinical Applications of Zirconia

The use of zirconia has grown significantly among various dental applications, including:

- **Zirconia-Based Crown and FDP:** Zirconia is a widely used material in fixed dental prosthodontics because of its mechanical strength, high toughness, and good chemical stability, which make it ideal ceramic material for bearing the heavy occlusal forces that are common in the posterior region. Zirconia ceramics can be milled as a monolithic restoration or as a bilayered structure composed of a milled substructure and either a manually layered, hot-pressed, or CAM-designed veneering ceramic adhered to the coping. Clinically, zirconia restorations are commonly classified into monolithic (fully sintered) zirconia and layered zirconia restorations. In monolithic zirconia, the restoration is fabricated entirely from zirconia, whereas in layered zirconia a zirconia core is veneered with a ceramic layer to improve esthetics. Most zirconia materials used in CAD/CAM systems are milled in a pre-sintered (soft) state (e.g., KATANA™ zirconia, Kuraray Noritake, Japan; IPS e.max ZirCAD, Ivoclar Vivadent, Liechtenstein), followed by final densification through high-temperature sintering. Alternatively, zirconia can also be milled in a fully sintered state (*e.g*., KaVo Everest ZH blanks; KaVo Dental, Germany), although this approach requires more robust machining and is less commonly used. Recently, additive manufacturing techniques, such as 3D printing of zirconia, have also been investigated as alternative fabrication methods; however, this technology is still under development and requires further research before widespread clinical application (Kelly & Benetti, 2011). Milling of zirconia in the pre-sintered state is generally preferred over milling fully sintered zirconia because it requires less machining force, reduces milling time, and is more cost-effective. In addition, machining fully sintered zirconia may introduce surface flaws that could influence the long-term strength of the material. Additionally, zirconia FPDs can replace missing teeth in the posterior regions with successful long-term clinical results (Tinschert *et al.*2007; Sailer *et al.*2015).

- **Zirconia-Based Dental Posts:** The demand for more esthetic root canal posts, particularly with all-ceramic restorations, has prompted the development of new post materials. When restoring anterior teeth with all-ceramic crowns, metal posts can lead to undesirable esthetic outcomes, such as the grey discoloration of the crowns and the adjacent gingival margin. Moreover, corrosion from prefabricated metal posts can cause complications. These issues have driven the innovation of white or translucent posts made from zirconia and other ceramic materials. Many studies investigated the use of zirconia posts, and they reported that the zirconia post showed a high success rate (Kakehashi *et al.*1998). Likewise, another clinical study investigated zirconia posts and observed good clinical success of zirconia posts with direct composite cores after a mean clinical service of 4.7 years (Paul & Werder, 2004). Despite the advantages of zirconia posts with respect to esthetics and biocompatibility, they have some limitations. Zirconia posts are stiff without any ductility; they may present challenges in small sizes and when retreatment is required. Additionally, they have poor retention to the resin core in comparison to the glass fiber reinforced posts posts (Purton *et al.*2000; Asmussen *et al.*1999; Butz *et al.*2001).
- **Zirconia-Based Implant Abutments:** Zirconia is also used as an implant abutment due to its strength, biocompatibility, and ability to integrate well with soft and hard tissues. Zirconia abutments offer an esthetic alternative

to metal abutments, particularly in the anterior region. Zirconia abutments can be custom milled by CAD/CAM technology in the laboratory and bonded on titanium bases for screw fixation. The main argument for the use of zirconia abutments is that its non-metallic appearance can enhance better color matching in the esthetic zone, especially with the increasing use of all-ceramic crowns. (Yildirim *et al.*2000; Yildirim *et al.*2003; Guess *et al.*2002). There are many studies that investigate the survival rate of zirconia abutments with alumina abutments; they reported a high survival rate of 100% for zirconia abutments without fracture (Glauser *et al.*2004; Volz & Blaschke, 2004). While other *in vitro* studies have proven titanium abutments to have preferable fracture resistance to zirconia abutments (Att *et al.*2009). Furthermore, a clinical study reviewed the utility of zirconia in fixed implant prosthodontics. The authors concluded that the clinical long-term success of zirconia in fixed implant prosthodontics is questionable as a result of the fracture of the veneering ceramics (Guess *et al.*2002). Due to a broad variety of results from clinical studies, zirconia abutments and implant-supported fixed restorations should be further evaluated before any recommendations of implant supported zirconia restorations for use in routine practice can be given.

- **Zirconia-Based Esthetic Orthodontic Brackets:** In addition to the dental applications zirconia has also been applied for the fabrication of esthetic orthodontic brackets. Zirconia brackets have gained interest, since zirconia reportedly has the greatest toughness and is cheapest amongst all ceramics (Kusy, 2002). In clinical orthodontics, stainless steel brackets remain the most widely used, whereas esthetic alternatives include polycrystalline and monocrystalline alumina (sapphire) brackets as well as polycarbonate brackets. However, Keith *et al.* (1994) reported no significant advantage of zirconia brackets over polycrystalline alumina brackets with regard to their frictional characteristics. Further clinical studies are needed to investigate the use of zirconia in the orthodontic field.

2.2.3 Bonding of Zirconia Restorations

The bonding of zirconia has been extensively studied due to its inert properties, which complicate adhesive bonding. The absence of a glassy matrix means that zirconia is free from silica and, as a result, cannot be conditioned with conventional acid etching techniques which limits the formation of chemical bonds with dental adhesives. This is an important distinction from glass-ceramic materials (Zarone *et al.*2011; Zarone *et al.*2006).

Conventional cement can be used if the abutment has adequate resistance and retention. However, when there is insufficient retentive form, the zirconia restoration must be bonded using a resin cement. A zirconia restoration can be bonded to the tooth structure if a meticulous bonding protocol is followed (Inokoshi *et al.*2014). The bonding protocol is a combination of mechanical and chemical pretreatment. Therefore, surface pretreatments to modify the zirconia surface and improve bonding are crucial. The mechanical pretreatment involves air-borne particle abrasion with 50 µm Al_2O_3 particles at 2.5 bar pressure for 10 s at a 10 mm standoff distance. This method has been shown to improve the retention of resin cement. By increasing surface roughness, air abrasion enhances mechanical interlocking. While the chemical pretreatment involves using a ceramic primer that contains silane and a 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP) monomer, which can chemically bond to zirconium oxide surfaces and improve the durability of adhesion (Blatz *et al.*2016; Papia *et al.*2014; Sulaiman *et al.*2023). The combination of mechanical and chemical treatments on zirconia surfaces has demonstrated good outcomes; specifically, the application of primers and adhesion-promoting agents containing acidic monomers (10-MDP) can exert a synergistic effect with silane coupling agent, enhancing the efficacy of simplified adhesive techniques (Zarone *et al.*2019; Srikanth *et al.*2015, Pilo *et al.*2018). An adhesive or self-adhesive resin cement is used to bond the zirconia to the tooth structure. Selecting the appropriate resin cement is essential for establishing a strong bond with zirconia restorations. The cement must have both good adhesive properties and the ability to withstand masticatory forces and thermal stresses in the oral environment. Self-adhesive cements have the advantage of simplicity and reduced procedural steps, which do not require an additional bonding agent. This cement has been shown to provide adequate bond strength to zirconia. However, they often have lower bond strengths than adhesive cements that require a separate adhesive system, including the use of a bonding agent and a dual-cured resin cement (Zarone *et al.*2019; Papia *et al.*2014). The bond strength of zirconia restorations using various bonding techniques has been studied in many different studies. It has been consistently demonstrated that surface pretreatment plays a critical role in the success of zirconia bonding.

Studies indicate that grit-blasting, when succeeded by the application of a silane coupling agent or a designated zirconia primer, yields superior bond strengths relative to untreated zirconia surfaces. Furthermore, the application of dual-cured or light-cured resin cements, coupled with appropriate surface pretreatment, has resulted in favorable clinical outcomes, including diminished failure rates in longitudinal studies. (Zarone *et al.*2019; Papia *et al.*2014; Luthra & Kaur, 2016; Pilo *et al.*2018). By combining mechanical and chemical surface pretreatments, along with the appropriate choice of resin cement, clinicians can achieve reliable bonding that ensures the longevity and function of zirconia restorations. However, further research and long clinical studies are needed to improve bonding and to optimize the performance of zirconia in restorative dentistry.

2.3 Lithium Disilicate Glass-ceramics in Dentistry

2.3.1 Properties of Lithium Disilicate Glass-Ceramics

The utilization of glass ceramics in dentistry has been ongoing since the 1950s, when researchers began to explore the possibility of combining glass and ceramics to improve the material's mechanical properties. With ongoing advancements and enhancements in bonding techniques and materials, as well as material properties (McLean & Hughes, 1965; Grossman, 1985). In 2005, the all-ceramic IPS e.max system (Ivoclar Vivadent), containing lithium disilicate, was introduced, setting new standards for both its optical and mechanical performance. The primary components of crystalline phase of lithium disilicate glass-ceramics are lithium oxide (Li_2O) and silica (SiO_2). It is a highly crystalline material containing ~70 vol% of elongated lithium disilicate crystals and glass matrix (Zhang & Kelly, 2017). High mechanical strength and exceptional esthetic properties are both attributed to this composition. The IPS e.max glass ceramics, for example, are available in two forms, press and CAD, reflecting differences in processing conditions. The IPS e.max Press ingots undergo heat pressing at 920°C for a duration of 20 min. For the IPS e.max CAD™ ingots undergo initial heat treatment to form an intermediate lithium meta-silicate glassceramic, facilitating machining into the desired shape. The CAD blocks are subsequently subjected to a crystallization firing cycle at approximately 840–850 °C, during which the lithium metasilicate phase is converted into lithium disilicate. Although the holding time at peak temperature is typically around 7–10 min, the complete crystallization cycle generally lasts approximately 20–25 min, depending on the furnace program (Kelly & Benetti, 2011). In modern dentistry, lithium disilicate has become an innovative material, especially for restorative applications such as veneers, crowns, FPDs, and inlays/onlays.

Lithium disilicate materials have strong mechanical and flexural strength, superior wear resistance, and exceptional beauty. "IPS e.max Press" (Ivoclar Vivadent) demonstrates a flexural strength of 370–460 MPa and a fracture toughness of 2.8–3.5 $MPa \cdot m^{1/2}$, significantly higher than that of older glass-ceramics (Fischer *et al.*2005; Denry & Holloway, 2010). The higher mechanical performance of this material arises from two factors: firstly, the layered, tightly interlocked structure of elongated disilicate crystals, which inhibits crack propagation across the planes; secondly, a difference between the thermal expansion coefficients of lithium disilicate crystals and the glassy matrix, which generates tangential compressive stress around the crystals. Partially pre-crystallized blocks for IPS e.max CAD™ are produced in a "blue state," including 40% metasilicates with lithium disilicate crystal nuclei. These blocks have a moderate flexural strength of around 130 MPa, leading to enhanced cutting efficiency, improved workability, and reduced wear on milling devices. The milling process occurs in the pre-crystallized state, followed by a heating cycle (840°-850°C for 10 min) that converts metasilicate crystals into lithium disilicate (~70%), enhancing the flexural strength to 262 ± 88 MPa and yielding a fracture toughness of 2.5 MPa·m$^{1/2}$. The difference in flexural strength of lithium disilicate between heat-pressed and CAD-CAM blocks with varying translucency remains controversial. The flexural strength of IPS e.max Press and IPS e.max CAD™ was found to be similar, and the manufacturing process seemed to have no impact on the mechanical properties of lithium disilicate ceramics; additionally, translucency significantly affected the flexural strength only CAD-processed materials (Fabian *et al.*2017; Zarone *et al.*2016; Zhang & Kelly, 2018).

In addition to high mechanical properties, lithium disilicate glass-ceramics is known for its exceptional optical properties. Lithium disilicate restorations offer impressive translucency, which mimics the appearance of natural teeth. This is particularly important in esthetic dentistry, where achieving a natural look is paramount. The material's optical properties allow for effective light transmission and reflection, resulting in restorations that blend seamlessly with the surrounding teeth. Thus, these optical properties make it ideal for anterior restorations such as veneers and crowns, where esthetic is a critical factor (Heintze *et al.*2008). One of the critical optical properties of lithium disilicate is its translucency, which contributes significantly to the material's ability to mimic natural tooth structure.

Translucency defines the ability of a material to transmit light, allowing underlying dental tissues or structures to be seen through the restoration. There are numerous factors that affect the translucency of lithium disilicate restorations, including: thickness of the material, it is well-known that the translucency of certain restorative materials decreases as the thickness increases, due to the fact that the transmitting light faces more difficulty passing through thicker materials compared to thinner ones, and different thicknesses are required within a restoration depending on anatomy and preparation (Brodbelt *et al.*1980; Chu *et al.*2007; Heffernan *et al.*2002; O'Keefe *et al.*1991; Ozturk *et al.*2008; Yu & Lee,2009). Other factors include firing and processing conditions (Ozturk *et al.*2008), luting agent (Barath *et al.* 2003; Terzioglu *et al.* 2009; Wang *et al.*2011), background shade (Barath *et al.*2003; Li *et al.*2009; Spyropoulou *et al.*2011), surface texture and polishing (Wang *et al.*2011), and illuminant (Yu & Lee, 2009). Several techniques have been developed to evaluate the translucency of lithium disilicate materials.

The most common methods involve measuring the translucency parameter (TP) and contrast ratio (CR) (Johnston *et al.*1995; Shono & Nahedh. 2012; Wang *et al.*2013; Baldissara *et al.*2018; Shirani *et al.*2021; Vichi *et al.*2023). IPS emax's CR at 1 mm thickness is 0.78, and its TP is 17.8 (Wang *et al.*2013; Barizon *et al.*2013). The translucency of IPS e.max is more than that of zirconia (Baldissara *et al.*2010). The development of lithium disilicate glass-ceramics has had a profound impact on restorative dentistry, offering patients and practitioners alike a material that combines strength, esthetics, and longevity. Despite their favorable esthetic and adhesive properties, glass-ceramics such as lithium disilicate present certain limitations. Their flexural strength and fracture toughness are lower than those of zirconia ceramics, which may restrict their use in high-stress areas or long-span fixed dental prostheses. Consequently, lithium disilicate is commonly indicated for single crowns, veneers, inlays, and onlays, particularly in the anterior region where esthetics are critical. In contrast, zirconia ceramics, owing to their superior mechanical strength and fracture resistance, are often preferred for posterior restorations and multi-unit fixed dental prostheses (Kelly & Benetti, 2011; Zhang & Kelly, 2017; Sailer *et al.* 2015). With ongoing advancements in technology and materials science, lithium disilicate glass-ceramics will likely remain at the top of dental restoration options, continuing to meet the evolving needs of modern dentistry.

2.3.2 Bonding of Lithium Disilicate Restorations

In addition to high mechanical properties and excellent optical properties, lithium disilicate ceramics exhibit great adhesion to tooth structure. This strong adhesion is mainly attributed to the presence of a silica-based glass matrix, which allows the ceramic surface to be etched with hydrofluoric acid, creating micromechanical retention. Furthermore, the application of silane coupling agents promotes chemical bonding between the ceramic surface and resin-based luting materials. Lithium disilicate restorations can be effectively bonded to the tooth using modern adhesive systems, which enhances retention and reduces the risk of microleakage. The strong bond also improves the overall strength and longevity of the restoration. Furthermore, due to the presence of silica, Li-disilicate glass-ceramics is classified as hydrofluoric acid (HF)-sensitive ceramics, which is anticipated to exhibit a high adhesion strength to the substrate, attributed to both micromechanical and chemical bonding mechanisms. Effective surface treatment is crucial for establishing a lasting connection to lithium disilicate restorations. The micromechanical interlocking between ceramics and resin cement at the intaglio surface relies on the formation of surface microirregularities and roughness through different surface pretreatment techniques, including hydrofluoric acid (HF) etching, physical treatments such as alumina particle grit-blasting or diamond bur grinding, and laser treatments. However, diamond bur grinding is less commonly used as a pretreatment method because it may create irregular surface defects and microcracks in brittle ceramic materials, potentially compromising their mechanical strength and increasing the risk of crack propagation.

Currently, HF etching is the best-established and most used method for etching lithium disilicate restorations, taking into consideration both acid concentration and etching duration. This process selectively dissolves the silica-based glass matrix through a chemical reaction between hydrofluoric acid and silicon dioxide, producing soluble fluorosilicate compounds. As a result, lithium disilicate crystals become exposed and surface microporosities are created, which enhance micromechanical bonding with resin-based luting materials. For lithium disilicate ceramics, 20s HF etching (at 5% concentration) is recommended based on manufacturer instruction (Alex, 2008). Over-etching and higher HF concentrations (9–10%), can lead to the dissolution of crystals, and causing significant damage, not only to the surface but also to the internal microstructure of the material negatively impacting the bond and mechanical strengths, as well as long-term success of ceramic restorations (Murillo-Gómez *et al.*2018; Prochnow *et al.*2018; Sundfeld *et al.*2018). Other techniques for creating surface microirregularities in lithium disilicate ceramics include grit-blasting with aluminum oxide particles and laser etching. However, this pretreatment approach should be applied cautiously because ceramics are inherently brittle materials. Excessive grit-blasting may introduce surface defects or microcracks, which could reduce the mechanical strength of ceramic restorations and increase the risk of chipping or fracture. Research indicates that these techniques may result in excessive material loss and produce surface modifications that are less uniformly distributed compared to hydrofluoric acid etching, potentially leading to a significant reduction in flexural strength (Ataol & Ergun, 2018; Menees *et al.*2014).

In addition to micromechanical interlocking, chemical bonding between the ceramic surface and the adhesive materials is essential for the bonding of ceramic restorations. The bonding of lithium disilicate restorations is efficiently increased by using silane coupling agents. A silane coupling agent is a bifunctional molecule that promotes chemical bonding between the silica-based ceramic surface and the organic resin matrix of the adhesive material. The glass matrix in lithium disilicate ceramics can react with silane, forming siloxane (Si–O–Si) bonds between the ceramic surface and the coupling agent. In addition, the methacrylate functional group of the silane molecule can copolymerize with the resin matrix of the adhesive material, thereby creating a chemical bridge between the ceramic surface and the resin cement. Consequently, silane-mediated adhesion involves both chemical coupling with the ceramic surface and polymerization with the organic resin matrix, resulting in a durable ceramic–resin interface (Benetti *et al.* 2019; Matinlinna *et al.* 2018; Tian *et al.* 2014). Although both mechanisms contribute to durable adhesion, micromechanical interlocking produced by hydrofluoric acid etching is generally considered the primary contributor to bond strength, whereas chemical bonding provided by silane coupling agents further enhances the stability of the resin–ceramic interface. Several studies have highlighted the importance of using silane coupling agents to improve bond strength, particularly when the ceramic is treated with hydrofluoric acid (HF) to etch the surface and increase surface area (Blatz *et al.*2003; Carvalho *et al.*2014; Frankenberger *et al.*2015; Carvalho *et al.*2016). The clinical bonding protocol for lithium disilicate restorations generally involves several sequential steps. The internal surface of the ceramic restoration is first etched with hydrofluoric acid, followed by thorough rinsing and drying. Subsequently, a silane coupling agent is applied and allowed to react with the ceramic surface before gentle air drying. Afterward, resin cement is applied and the restoration is seated and polymerized. During clinical try-in procedures, the intaglio surface may become contaminated with saliva. Therefore, it is recommended to clean the ceramic surface with phosphoric acid, followed by rinsing, drying, and reapplication of the silane coupling agent prior to final cementation to ensure optimal bonding (Blatz *et al.* 2003; Papia *et al.* 2014).

Additionally, it has been shown that the use of silane combined to a phosphate functional monomer, 10-Methacryloyloxydecyl-Dihydrogen-Phosphate (10-MDP), can further improve the bond strength of resin-based luting cements to lithium disilicate ceramics. The phosphate group of 10-MDP is capable of interacting with metal oxide surfaces, while the methacrylate group copolymerizes with the resin matrix of the adhesive system, thereby enhancing the stability of the resin–ceramic interface (Taguchi *et al.*2018).

The choice of adhesive system is crucial too for achieving strong bonding to lithium disilicate restorations. Adhesive resin systems are generally classified into total-etch (etch-and-rinse) and self-etch systems. In total-etch systems, the tooth surface is first conditioned with phosphoric acid to remove the smear layer and demineralize enamel and dentin, followed by the application of primer and adhesive resin. In contrast, self-etch systems contain acidic functional monomers that simultaneously condition and prime the tooth surface without the need for a separate phosphoric acid etching step. Total-etch adhesives have been shown to provide high bond strengths when combined with hydrofluoric acid etching and silane treatment of lithium disilicate ceramic surfaces. However, they can be technique-sensitive, requiring precise application and timing (Blatz *et al.*2003; Johnson *et al.*2018; Mobilio *et al.*2015). While self-etch adhesives simplify the bonding procedure by eliminating the need for separate etching steps. Research suggests that self-etch adhesive bond strength values decrease over time and may provide lower bond strength compared to total-etch systems, particularly in areas requiring high bond strength. However, some studies have shown that total-etch systems, combined with

HF and silane treatment, often result in superior bond strength (Blatz *et al.*2002; Peumans *et al.*2005; Mobilio *et al.*2015; Stewart *et al.*2002; Cardoso *et al.*2011).

Bonding lithium disilicate restorations require careful consideration of surface pretreatment, adhesive choice, and clinical technique. By refining bonding techniques and understanding the material's behavior, clinicians can achieve durable and esthetically pleasing outcomes with lithium disilicate restorations.

2.4 Laser Technology in Dentistry

The concept of using lasers in dentistry dates back to the 1960s, when Miaman first introduced the ruby laser for dental application in 1960. Leon Goldman, a pioneer in laser medicine, has reported on the biomedical aspects of lasers and has also recorded findings in laser dentistry, mainly on the effects of lasers on dental caries, teeth, and other tissues in 1963 (Convissar 2015). Since then, researchers and practitioners have explored different types of lasers and their various applications in dental practice. Over the decades, the development of laser systems in dentistry has expanded, offering multiple options for both hard and soft tissue management (Verma *et al.*2012). A laser emits a wavelength of light that interacts with different oral tissues in specific ways depending on the wavelength. These wavelengths can be absorbed, scattered, or reflected upon interacting with oral tissues. This interaction between laser wavelength and oral tissues yields multiple therapeutic effects, including cutting, coagulation, ablation, and photobiomodulation (Convissar, 2015). Table 1 summarizes different types of lasers are used in dentistry, each laser type has distinct characteristics, wavelengths, and tissue interactions that make it suitable for particular procedures such as the following:

- Hard Tissue Lasers: such as Er:YAG (Erbium Yttrium-Aluminum-Garnet) and Er,Cr:YSGG (Erbium, Chromium: Yttrium Scandium Gallium Garnet) lasers, are primarily used for procedures involving dental hard tissues, including enamel, dentin, and bone**.** These lasers are commonly applied for cavity preparation, caries removal, enameloplasty, and more recently for the removal of ceramic restorations. They operate at wavelengths that are highly absorbed by water and hydroxyapatite, allowing precise and efficient removal of dental hard tissues while minimizing thermal damage to surrounding structures. Soft Tissue Lasers: such as diode lasers, Nd:YAG (Neodymium-doped Yttrium Aluminum Garnet), and CO_2 lasers, are commonly used for gingival surgery, periodontal therapy, frenectomy, and soft tissue biopsies. These lasers offer excellent hemostatic properties, minimal trauma to adjacent tissues, and reduced postoperative discomfort for patients.

Table 1. Comparison between different types of lasers used in dentistry.

Laser type	Wavelength (nm)	Primary applications
Er:YAG	2940 nm	Hard tissue (tooth, bone)
Er,Cr:YSGG	2780 nm	Both hard and soft tissues (tooth, bone)
Diode	800–980 nm	Soft tissue (gingiva)
CO2	10,600 nm	Soft tissue (gingiva)
Nd:YAG	1064 nm	Both hard and soft tissues (gingiva, bone)

2.4.1 Erbium Lasers in Dentistry

Erbium lasers, particularly the Er:YAG, were first introduced in the early 1990s when researchers began investigating their use for soft and hard tissue. Since their initial introduction for dental use, Er:YAG lasers have been increasingly utilized in dental practice and are becoming more commonly used. Many technological advancements enabled it to be used successfully for hard tissue procedures in dentistry.

The Er:YAG laser received the U.S. Food and Drug Administration (FDA) approval for dental applications in 1997, which was a significant milestone in the field of laser dentistry. Its efficacy and safety have been proved by a multitude of studies over the years, resulting in an increase in its use in clinical settings (Bader & Krejci, 2006).

The Er:YAG laser systems consist of a laser medium, including the core of the Er:YAG laser having the erbium-doped crystal that serves as the laser medium. Erbium ions are incorporated into an yttrium-aluminum-garnet (YAG) crystal, allowing it to emit light at a wavelength of 2940 nm. The laser medium is activated using an optical pumping system, commonly using flashlamps or diode lasers. This energy stimulates the erbium ions, resulting in the emission of photons. The laser beam is transmitted through a delivery system, potentially including optical fibers or handpieces. At the end of delivery system, a handpiece and a small-diameter glass tip concentrate the laser energy down to a convenient surgical size, approximately 0.5 µm with air and water spray are provided for dental procedures. This system enables precise targeting of laser energy to the treatment zone (Van, 2004).

2.4.2 Mechanism of Action of Er:YAG Laser

The Er:YAG laser emits light at a wavelength of 2940 nm, which is significantly absorbed by water and hydroxyapatite, the mineral component of tooth structure. The Er:YAG wavelength at 2940 nm exactly matches the absorption peak of water, which is also absorbed by hydroxyapatite. Therefore, the Er:YAG laser is an optimal tool for hard tissue removal, as it interacts with the water content in dental tissues, enabling precise cutting without the thermal damage frequently associated with conventional mechanical tools (Bader & Krejci, 2006). The penetration depth of the Er:YAG is only a few micrometers. The superficial layer of Er:YAG laser penetration can be promptly heated, causing the pressure within the irradiated volume to exceed the material's strength. The overheated water rapidly vaporizes, and the resulting vapor transfers adjacent fragmented tissue into a thermomechanical ablation process.

Increasing power accelerates the ablation process, resulting in a reduction in thermal side effects while simultaneously increasing mechanical side effects (Hibst, 2002; Paghdiwala *et al.*1993). The shorter the pulse length, the lower the energy density needed for ablation. The ablation threshold of Er:YAG lasers ranges between 6 J/cm^2 for 100 μs pulses and 10 J/cm^2 for 700 μs pulses (Apel, 2002). Thus, the Er:YAG laser is the most effective system for the removal of hard dental tissue.

2.4.3 Uses of Er:YAG Laser in Dentistry

1. Hard Tissue Applications

- The Er:YAG laser is widely utilized for cavity preparation: the Er:YAG can be safely used for class I, II, III, IV, and V dental preparations. Due to its wavelength (2940 nm), which is strongly absorbed by water and hydroxyapatite. This allows for precise ablation of enamel and dentin through a process called thermomechanical ablation. Its high affinity for water allows it to effectively ablate enamel and dentin with minimal thermal damage and no mechanical vibration. Additionally, Er:YAG lasers have demonstrated the ability to make preparations in enamel and dentin with greatly reduced local anesthetic or no anesthetic at all without discomfort to patients due to pain, noise, and vibrations, unlike the preparation of teeth by way of traditional methods using high-speed and low-speed handpieces (Cozean & Powell, 1998; Den Besten *et al.*2001; Van, 2004).
- Removal of Carious Lesions: The Er:YAG laser can be used as an effective tool for caries removal while preserving healthy tissue. This results in more conservative and biologically respectful treatment. The laser eliminates carious lesions through thermo-mechanical ablation, wherein the rapid heating of water in the affected area induces micro-explosions that gently ablate the diseased tissue while preserving the

adjacent healthy tissue, unlike the traditional rotary cutting instruments (Aoki *et al.*1998; Nammour, 2012).

- Etching of Enamel and Dentin: the Er:YAG laser etching can replace or complement traditional acid etching. When an Er:YAG laser is applied on enamel or dentin, it eliminates mineral content through a micromechanical process, resulting in a rough, irregular surface that enhances resin bonding. In contrast to acid etching, which chemically demineralizes the surface, laser treatment alters it through micro-ablation, exposing the collagen network in dentin and opening enamel prisms without excessive demineralization. Thus, the Er;YAG laser produces a clean, dry surface ideal for bonding restorative materials, especially in adhesive dentistry (Martinez-Insua, 2000; Hibst, 2002).
- Bone Surgery: the Er:YAG laser is used for cutting and contouring bone tissue due to the wavelength's affinity for the composition of osseous tissue and through thermo-mechanical ablation. Unlike rotary instruments, the laser does not rely on mechanical contact, resulting in less trauma to surrounding tissues, minimal invasiveness, no bleeding, andwith reduced risk of thermal necrosis due to water cooling and minimal heat generation (Bornstein & Lomke, 2003; Bader & Krejci, 2006).

2. Soft Tissue Applications

   The Er:YAG laser is not only highly effective on hard tissues, but it is also highly valuable for soft tissue procedures in dentistry. The Er:YAG laser ablates soft tissue through the same mechanism as hard tissue, as demonstrated by laser physics and absorption curves of various tissues. The infrared beam's laser energy is transformed into local thermal energy, which induces a substantial expansion of the target chromophore in water. The resulting micro-explosions result in thin layers of tissue ablation with minimal thermal damage, making it a versatile and patient-friendly tool in oral soft tissue surgeries like gingivectomy, frenectomy, and periodontal procedures. Therefore, the Er:YAG laser is considered a safe, effective, and minimally invasive tool for a wide range of soft tissue procedures in dentistry (Lee, 1998; Bader & Krejci, 2006). In periodontal therapy, the Er:YAG laser can be utilized for debridement of root surfaces, removal of calculus without damaging the cementum, pocket disinfection through its bactericidal effect, and stimulating tissue regeneration when used in laser-assisted periodontal therapy (Schwarz *et al.*2001; Aoki *et al.*2000).

3. Endodontics Therapy

   In endodontic applications, the Er:YAG laser has shown promising results, particularly in the disinfection and debridement of root canals. Er:YAG laser has a bactericidal effect and thus, can be used to help reduce and eliminate the bacteria and infected tissues in the root canal treatment while preserving the adjacent healthy tissues (Hedge, 2018). Furthermore, the thermal disinfection capabilities of Er:YAG lasers can assist in the elimination of microbial contaminants and biofilms within the root canal, thereby reducing the likelihood of postoperative infections (Galui, 2019). The long-term prognosis of endodontic procedures is improved by the precise and controlled nature of laser treatment, which enables the thorough cleaning and shaping of the root canal system (Folwaczny *et al.*2003; Hedge *et al.*2018).

4. Teeth Whitening

   It is important to distinguish between tooth whitening and tooth bleaching. Tooth bleaching refers to the chemical lightening of tooth color using oxidizing agents such as hydrogen peroxide, whereas tooth whitening is a broader term that includes any procedure that improves tooth appearance by removing stains or restoring the natural tooth color.

   Er:YAG Laser can also be used to enhance teeth bleaching procedures. In laser-assisted whitening, the Er:YAG laser emits light that is absorbed by the water content in the bleaching gel. This energy heats the gel, accelerating the chemical breakdown of hydrogen peroxide into reactive oxygen species. These oxygen molecules penetrate the enamel and oxidize pigmented molecules, leading to a whitening effect. Therefore, the Er:YAG laser can be an effective adjunct for in-office teeth whitening, providing faster and more efficient activation of bleaching agents with minimal risk of thermal damage (Bader & Krejci, 2006).

5. Er:YAG Laser for Ceramic Crown Retrieval

   Er:YAG laser has emerged as an innovative and minimally invasive tool in modern dentistry, particularly for the removal of ceramic restorations such as crowns and veneers. Operating at a wavelength of 2940 nm, the Er:YAG laser is highly absorbed by water and hydroxyapatite, making it suitable for hard tissue procedures and adhesive resin degradation. The process of ceramic crown removal is often challenging due to the strong bond between the ceramic material and the tooth surface, especially when resin-based cements are used. The Er:YAG laser facilitates the removal of ceramic crowns by targeting the water molecules within the luting cement (typically resin-based). The laser energy is absorbed by the water content in the cement, causing micro-explosions that break down the adhesive layer between the tooth structure and the crown. This results in debonding of the restoration without damaging the underlying tooth or restoration (Coluzzi & Convissar, 2004; Convissar, 2016).

2.4.4 Previous Studies on Erbium Laser Retrieval of Ceramic Restorations

Removing bonded all-ceramic restorations conventionally by using rotary instruments is time-consuming and destructive to the restoration. Erbium-family lasers –the Er:YAG (2940 nm) and erbium, Er,Cr:YSGG (2780 nm) –have emerged as promising minimally invasive tools for debonding ceramic crowns and veneers. These lasers emit mid-infrared pulses that are well absorbed by water and certain resin components, allowing energy to transmit through ceramic materials and target the resin-based luting cement. The laser energy causes degradation of the cement through thermal softening, ablation, or microexplosions of water at the cement interface without significant cutting of the crown itself (Rechmann *et al.*2014). Several studies have demonstrated the efficacy of the Er:YAG laser in removing lithium disilicate and zirconia crowns. However, the efficacy of laser debonding depends on various factors, including the type of ceramic, thickness of ceramic, cement, and laser parameters. Studies using *in vitro* spectroscopy have established distinct how erbium laser energy interacts with cements and ceramics. Rechmann *et al.*2014, particularly demonstrated using the Fourier Transform Infrared Spectroscopy (FTIR) spectroscopy and power transmission measurements that Er:YAG laser light can penetrate common dental ceramics and be absorbed by underlying resin cements. In that study, specimens of lithium disilicate (IPS e.max CAD™) and leucite-reinforced glass ceramic (IPS Empress Esthetic) transmitted roughly 21–60% of incident Er:YAG energy; a zirconia ceramic (IPS e.max ZirCAD) transmitted only approximately 5–10%. Though zirconia transmits less, the energy it transmitted was still enough to ablate resin cement under it. With first cement breakdown happening at fluences about 1.3–2.6 J/cm^2, all tested resin cements revealed significant absorption at 2940 nm due to their resin matrix and water content. Though higher energy or longer exposure could be required for less-transmissive ceramics like zirconia, these results verify that erbium laser energy can reach and disturb the bonding cement through several ceramic types.

Material characteristics, particularly ceramic type and thickness, play a significant role in this process. Lithium disilicate, glass-ceramic is more translucent and enables deeper laser energy penetration than polycrystalline zirconia ceramic.

Consequently, many studies have reported that lithium disilicate restorations exhibit faster debonding times than zirconia when subjected to comparable laser settings. For example, a recent laboratory study conducted by Jiang *et al.*2024 revealed that conventional 3Y-TZP zirconia required significantly more laser time to debond than highly translucent 5Y-TZP zirconia. This is primarily due to the former's lower light transmission. However, erbium lasers have been exhibited to be effective in the removal of highly sintered 3Y zirconia crowns, as evidenced by numerous studies. It is essential to acknowledge that erbium laser debonding is also effective for feldspathic porcelain veneers and other glass-based ceramics. Er:YAG has been proven to be capable of debonding porcelain veneers without compromising tooth structure in previous research Rechmann *et al.*2014. This has been further confirmed in recent years for newer ceramic systems (Morford *et al.*2011; Grzech-Leśniak *et al.*2020; Deeb *et al.*2021).

The type of luting cement is another critical factor. Erbium lasers are most effective on resin-based cements (including resin-modified glass ionomer, RMGIC) because these cements contain organic polymers and water that strongly absorb the laser energy (Rechmann *et al.*2014). Resin composite cements, such as Variolink™, Multilink™, and RelyX™ Unicem™, were used in nearly all studies conducted in the past decade to bond the ceramic restorations. The crown-to-tooth bond is weakened until the restoration can be removed by thermal softening or ablation of these cements under laser irradiation. By contrast, traditional zinc phosphate cement (inorganic, with no resin) is not commonly examined in laser debonding studies; it is expected to be less susceptible to 2940 nm laser energy due to minimal water/organic content. In fact, according to a clinical study, it reported that all crowns that were successfully laser-removed had been luted with resin-based or RMGI cements (Deeb *et al.*2023). An isolated case of a crown luted with a eugenol cement (ZOE) required mechanical assistance for removal, underscoring that laser debonding is best suited for resin-bonded restorations. In practice, if a crown cemented with a purely inorganic cement must be removed, lasers may be less effective, and conventional sectioning may still be required (Deeb *et al.*2023).

Additionally, several controlled *in vitro* studies have examined various laser settings on different ceramics to identify safe and efficient parameters for debonding. Most investigations employed extracted human teeth with cemented crowns or veneers to simulate clinical scenarios, measuring outcomes such as debonding time, temperature rise, and post-removal surface condition.

Laser parameters (energy, pulse rate, *etc.*) were found to critically affect performance. Er:YAG laser emits short pulses (50–400 µs) in the mid-IR and is commonly used with water spray cooling. Researchers have varied the laser's pulse energy (or power) and frequency to optimize debonding: higher energies generally speed up cement ablation but also risk greater heat generation. For instance, Gurney *et al.* (2016) conducted a pilot study on lithium disilicate crowns using an Er,Cr:YSGG laser at 3–5 W (approximately 50–84 mJ per pulse at 20 Hz). They found that 3.5–4 W was the optimal range for consistent crown removal –lower power sometimes failed to debond the crown, whereas higher power (5 W) offered no clear advantage in success rate. In their trial, about 40% of lithium disilicate crowns came off after the first 30-s laser application, and most others required a second 30 s application. No irreversible damage was noted to teeth or restorations, and the authors concluded that Er,Cr:YSGG lasers can safely remove lithium disilicate crowns with those settings. Notably, even at 4 W power, the total laser irradiation time per crown was around 60–90 s in successful cases significantly shorter than the ~6 min average needed to cut off similar crowns with rotary instruments.

Several recent studies have systematically explored optimal Er:YAG settings for zirconia versus glass-ceramics. Jiang *et al.*2024, bonded 200 zirconia specimens (3Y and 5Y types) to dentin with resin cement and tested a wide matrix of Er:YAG settings (80–260 mJ pulse energy at 10 or 20 Hz). They reported that pulse frequency (10 *vs* 20 Hz) did not significantly affect debonding efficiency, but higher pulse energy dramatically reduced the debonding time without raising the dentin temperature. On average, specimens were detached in ~59 s with an average temperature rise of only ~2.7°C. The optimal energies identified were 220 mJ for conventional 3Y-TZP zirconia and 200 mJ for more translucent 5Y zirconia, yielding debonding times as low as 5–10 s in some specimens. Crucially, no damage or phase changes in the zirconia were detected by microscopy or flexural strength testing after laser exposure. This indicates that properly tuned Er:YAG lasers can remove zirconia restorations rapidly without compromising their structural integrity.

Lithium disilicate ceramics, which are commonly used for veneers and crowns, have also been studied under varying Er:YAG power levels. Several studies have demonstrated that Er:YAG power directly influences the debonding time of lithium disilicate restorations. For instance, Ahrari *et al.* (2021) reported that higher laser energy significantly reduced the time required to debond lithium disilicate specimens while maintaining pulp-safe temperature levels and preserving the integrity of both tooth and restoration. Their study emphasized that increasing laser power enhanced the efficiency of lithium disilicate restoration debonding by reducing the time required for crown removal, but careful parameter optimization is required to avoid collateral thermal effects. The authors emphasize using adequate laser power to minimize procedure time and thermal risk, especially for thicker restorations. It is a frequent trend in many studies that shorter exposure times at higher power result in a lower temperature rise than lower-power settings used for extended durations. This counterintuitive finding is critical: quick and focused energy delivery minimizes heat conduction to the pulp, as demonstrated in the study by Morford *et al.*(2011), where optimized high-power Er:YAG settings maintained intrapulpal temperatures within safe limits, often below the critical 5.5°C threshold for pulpal damage.

Zirconia crown removal with lasers commonly requires higher energy input or longer irradiation than glass-ceramics, due to zirconia's opacity. A preliminary study by Gozneli *et al.*2023 examined different Er:YAG power levels for crowns of varying thickness. Full-contour lithium disilicate crowns of 1 mm, 1.5 mm, or mixed thickness were cemented on teeth and irradiated at 5.0 W, 5.6 W, or 5.9 W (with water cooling). The thinnest crowns (1 mm) could be safely debonded at 5 W, but thicker crowns required a maximum of 5.9 W for effective removal. At 5.9 W, all crowns eventually debonded, but if the crown was very thin the pulp temperature frequently exceeded the 5.5°C safety threshold. For 1.5 mm and multi-thickness crowns, 5.9 W was both effective and did not overheat the pulp, with median removal times of ~6–9 min. At lower powers (5 W, 5.6 W), those thicker crowns could not be removed even after 15 min of irradiation. These results mirror clinical intuition: higher laser power is needed for thicker or less translucent ceramics but must be moderated for thinner restorations to avoid thermal injury. The study concluded that Er:YAG crown retrieval is effective so long as the operator selects an appropriate power setting based on crown thickness, balancing speed and safety. Across these *in vitro* studies, a consistent outcome is that laser-assisted debonding causes minimal or no damage to the restoration or tooth surfaces. Scanning electron microscopy (SEM) analyses show largely unchanged ceramic and dentin surfaces after laser crown removal (Deeb *et al.*2021; Elkharashi *et al.*2020). For example, both Er:YAG and Er,Cr:YSGG lasers produced no visible cracking, charring, or enamel damage in retrieved crowns and tooth structure in multiple trials. The cement layer is typically found charred or disintegrated, confirming that the laser energy targets the bonding layer (Rechmann *et al.*2014). In some cases, a thin residue of cement remains on either the tooth or crown, which can be cleaned off, but the restorations themselves remain intact and often reusable (Deeb *et al.*2023). Maintaining the integrity of expensive ceramic prostheses is a significant advantage for clinicians who intend to reuse them.

Another primary concern in laser debonding is the temperature rise in the tooth. Excess heat (>5–6°C) at the pulp can potentially cause irreversible pulpitis. The evidence to date is reassuring that, with proper parameters and cooling, erbium laser crown removal stays within safe thermal limits. Rechmann *et al.*2015, was the first to investigate this in an *in vitro* tooth model. They observed an average intrapulpal temperature increase of only 5.4°C, with a range of approximately 3–12°C, when they used an Er:YAG laser (560 mJ pulses, 10 Hz, water mist) to remove lithium disilicate crowns. The authors concluded that Er:YAG debonding is pulp-safe, especially if the clinician intermittently pauses or moves the laser to allow heat dissipation and ensures water spray so that the intrapulpal temperature remains below the critical threshold for pulpal damage (~5.5 °C). Further research supports mild temperature elevations; for example, the investigation of debonding zirconia crowns by using two laser types, Er:YAG and Er,Cr:YSGG, revealed that the mean temperature increases for both lasers were only 1–2°C, which is significantly lower than the damaging thresholds (Deeb *et al.*2021). Even at higher laser powers, the total exposure time is short enough that heat does not accumulate dramatically (Morford *et al.*2011; Rechmann *et al.*2015; Ahrari *et al.*2021).

Additionally, teeth can be effectively cooled externally during laser use by air/water through the handpiece and rinsing; some protocols also suggest intermittently spraying the tooth from the opposite side with a dental syringe to further limit heating. All evidence from realistic models indicates safe temperature profiles, with pulpal ΔT usually below 5°C. Up to date, no negative pulpal consequences have been documented *in vivo* resulting from laser debonding (Deeb *et al.*2023).

The clinical application of laser debonding has seen significant advances in recent years. In a retrospective case series, Deeb *et al.* (2024) compiled data from 29 patients who underwent *in vivo* removal of a variety of ceramic prostheses using Er:YAG or Er,Cr:YSGG lasers. The cases consisted of 6 porcelain veneers, 7 lithium disilicate crowns, 30 zirconia crowns, and 3 multi-unit zirconia FPDs, all of which were luted with resin or RMGI cements. The results were overwhelmingly positive: 50 of the 52 abutment removals were successfully retrieved intact with the laser alone, amounting to over 95% of the restorations. Only two crowns fractured during removal due to a long-span zirconia FPD and a metal post interface, which necessitated the mechanical cutting for complete removal. The follow-up did not reveal any tooth injuries, including fractures or pulp necrosis. The reuse of numerous restorations is noticeable. For instance, all six veneers were removed and promptly re-cemented, and 17 of the 30 zirconia crowns have been reused either as-is or as temporary replacements. This emphasizes the practical advantage of lasers: they can preserve expensive restorations for reuse, thereby saving patients time and money.

The clinical laser parameters were consistent with those that were effective *in vitro*. In the afore mentioned studies, Er:YAG was commonly used at 2.5–5 W (12–16 Hz, 170–420 mJ) with Quantum Square Pulse/Super Short Pulse (QSP/SSP) pulse mode, which represent different laser pulse durations and energy delivery patterns. The Er,Cr:YSGG laser was used at 5 W and 15 pulses per second (pps) with water/air spray settings of 20/20% (Deeb *et al.*2023). The laser irradiation was applied to all crown surfaces (buccal, lingual, occlusal, and then angled into interproximal) for approximately 30 s per surface, which was a critical component of the protocol. Removal was then attempted, and the process was repeated if necessary. A moderate force was sufficient to dislodge the restoration in most cases, with a total irradiation of 1–3 min. This is consistent with the average clinical removal durations reported of lithium disilicate ceramic crowns take approximately 5.9 min, veneers take approximately 2.3 min, and zirconia crowns take approximately 7.1 min. These durations are comparable to or quicker than the process of cutting off crowns with a bur, which usually causes the restoration to be damaged and generally requires 5–10 min.

In addition, clinical limitations and considerations have also been noticed. First, laser crown removal necessitates an investment in laser equipment and training. Erbium lasers are expensive devices, and there is a learning curve involved in safely manipulating the laser around a restoration without directly ablating tooth structure. The dental team and patient must be safeguarded from laser exposure and debris. The high success rates were likely because the procedures were performed by experienced laser-certified dentists in the clinic. It is anticipated that this technique will become increasingly used in dental practice as more clinicians receive training.

Another factor to consider is that laser debonding is not suitable for all ceramics or clinical scenarios. Inefficient removal may result from extremely impermeable restorations, such as metal-ceramic crowns or zirconia with metal posts beneath, which block or dissipate laser energy (Deeb *et al.*2023). Lastly, it is imperative to adhere to safety protocols. Although pulp temperatures are generally safe, it is essential to consistently move the laser and prevent extended concentration on one area and to use a water spray when using a laser on a tooth, as heat can accumulate rapidly if the laser is used without water, as demonstrated by Rechmann *et al.*2015.

In summary, *in vitro* and *in vivo* studies have demonstrated that laser debonding is both safe and efficient and that it can significantly preserve both tooth structure and restorations when these precautions are observed. Although certain challenging scenarios persist, the applicability of laser technology and technique is being expanded by ongoing advancements. Nevertheless, *in vitro* temperature assessment methodologies may not fully replicate *in vivo* pulpal responses, heterogeneity in cements and ceramics (not all were evaluated), and lack of standardization in which studies varied considerably in laser settings (wavelength, pulse duration and cooling). To establish evidence-based guidelines for widespread clinical adoption and define optimized protocols, it is imperative to conduct additional standardized clinical trials and long-term *in vivo* evaluations.

2.4.5 Clinical Relevance and Gaps in Literature

From a clinical perspective, the use of Er:YAG laser irradiation for the retrieval of bonded ceramic restorations offers several advantages that align with current principles of minimally invasive and conservative dentistry. This technique facilitates the atraumatic removal of restorations such as crowns and veneers while preserving both the prosthesis and the underlying abutment structure. This is particularly beneficial in implant dentistry and esthetic zones, where restoration reuse or preservation of hard tissue is desirable. Unlike conventional rotary instrumentation, laser-assisted debonding minimizes mechanical trauma, reducing the risk of enamel or dentin over-preparation and postoperative sensitivity. Furthermore, the technique is generally associated with acceptable clinical removal times typically between two to eight min depending on the ceramic and cement type. Patients also report a high level of comfort during the procedure, reinforcing its suitability for modern clinical practice. Moreover, the ability to non-invasively retrieve restorations supports retreatment flexibility, allowing clinicians to maintain conservative strategies and accommodate future treatment modifications without compromising existing structures.

These clinical advantages correspond with the broader shift in restorative dentistry toward sustainable, adhesive-based treatments and digitally fabricated restorations. As CAD/CAM workflows and advanced ceramic systems continue to evolve, laser-assisted removal provides clinicians with enhanced control and procedural precision in prosthodontic care.

Despite promising developments, the current body of literature reveals several significant limitations that justify further investigation. Most of the available evidence stems from *in vitro* experiments or isolated clinical reports, which fail to replicate real-world conditions such as patient movement, posterior access limitations, salivary contamination, and operator variability. Randomized controlled trials (RCTs) comparing laser-based and conventional removal techniques under clinical conditions remain scarce. Moreover, the long-term outcomes of laser-treated cases, including pulp vitality, the durability of re-cemented restorations, and restoration survival following reuse, are insufficiently documented.

Another key limitation lies in the lack of standardized laser parameters. Across existing studies, considerable variability exists in settings such as pulse energy, frequency, pulse duration, and irradiation distance, which complicates comparisons and prevents the establishment of universal clinical guidelines. Although many contemporary erbium laser devices now offer proprietary pulse modes (such as QSP, SSP, and MSP), their effects on debonding efficacy have yet to be fully validated through comparative studies.

In addition, material-specific interactions remain underexplored. While lithium disilicate and zirconia have been the primary focus of research, there is limited data regarding other ceramics, including feldspathic porcelain, hybrid ceramics, and multilayered zirconia formulations. The influence of different luting agents such as bioactive cements, universal adhesives, and varying polymerization modes on laser efficiency and thermal behavior is also inadequately addressed in the literature.

Finally, broader economic and patient-centered outcomes are largely absent from the current discourse. While studies have addressed technical parameters such as debonding time and intrapulpal temperature changes, few have assessed cost-effectiveness or patient satisfaction. As a result, the long-term clinical and economic justification for adopting laser-based removal techniques remains uncertain.

In summary, while the application of erbium lasers for ceramic restoration retrieval is well supported from a technical standpoint, substantial gaps exist in clinical validation, parameter standardization, material-specific protocols, and holistic outcome assessments. These limitations form the basis for the present doctoral research, which aims to systematically investigate and address these unmet needs.

3 Aims

The research presented in this thesis is based on the working hypothesis that Er:YAG laser can be used to retrieve different ceramic restorations noninvasively without weakening materials' mechanical strength. It was also hypothesized that the type of luting cement does not influence laser retrieval capacity. Finally, it was hypothesized that laser treatment does not influence optical properties.

Accordingly, the following aims were established to:

1. Evaluate, compare, and contrast the time required for an Er:YAG laser to retrieve cemented crowns fabricated of different types of zirconia (3Y-TZP, 4Y-TZP, and 5Y-TZP) and lithium disilicate glass-ceramics (Study I).
2. Evaluate, compare, and contrast the time required for the Er:YAG laser to retireve zirconia and lithium disilicate crowns cemented with 2- and 1-bottle adhesive resin cement systems (Study II).
3. Investigate the effect of the Er:YAG laser on the inherent optical and mechanical properties of different zirconia (3Y-PSZ, 4Y-PSZ, and 5Y-PSZ) and lithium disilicate ceramics, and to determine material integrity post-removal to assess reusability potential (Study III).

4 Materials and Methods

4.1 Materials Used in the Studies

4.1.1 Ceramic Materials

The ceramic materials that were used in the experimental studies are listed in Table 2. In study II, 3 mol% yttria-partially stabilized zirconia (3Y-PSZ) specimens were used and compared to lithium disilicate glass ceramic material (IPS e.max CAD™ ,Ivoclar Vivadent AG; Schaan, Liechtenstein) of the following composition: SiO_2 in addition to Li_2O, K_2O, MgO, Al_2O_3, P_2O_5 and other oxides.

Table 2. The ceramic materials used in experimental studies.

Product name	**Shade**	**Yttria mol%**	**Manufacturer**
KATANA™ Zirconia High Translucent (Katana™ HT) HT10	A3	3% mol Yttria-partially stabilized zirconia (3Y-PSZ)	Kuraray Noritake Inc., Noritake, Japan
KATANA™ Zirconia Super Translucent Multi Layered (Katana™ STML)	A3	4% mol Yttria-partially stabilized zirconia (4Y-PSZ)	Kuraray Noritake Inc., Noritake, Japan
KATANA™ Zirconia Ultra Translucent Multi Layered (Katana™ UTML)	A3	5% mol Yttria- partially stabilized zirconia (5Y-PSZ)	Kuraray Noritake Inc., Noritake, Japan
IPS e. max CAD Low Translucency	A3	N/A	Ivoclar Vivadent AG, Schaan, Liechtenstein

4.1.2 Resin Cements

The adhesive resin cements used in studies I and II are listed in Table 3. These resin cements were selected because they represent widely used clinical adhesive systems with different bonding mechanisms and chemical compositions. In particular, they contain functional monomers such as 10-methacryloyloxydecyl dihydrogen phosphate (10-MDP), which are known to promote chemical bonding to ceramic materials and tooth structures. The inclusion of both self-adhesive and conventional adhesive resin cement systems allowed the evaluation of whether differences in cement chemistry influence the efficiency of laser-assisted crown retrieval.

In study I, self-adhesive resin cement Panavia^{TM} SA Cement Universal (Kuraray Noritake INC; Noritake, Japan) was used.

In study II, adhesive resin cements Panavia^{TM} V5 (Kuraray Noritake Dental Inc.; Tokyo, Japan) and RelyX™ Ultimate (3M ESPE; St. Paul, MN, USA) were used.

Table 3. Adhesive resin cements and their chemical compositions.

Product name	**Description**	**Manufacturer**	**Chemical Composition**	**Study**
Panavia™ SA	Self-adhesive universal resin cement	Kuraray Noritake Dental Inc; Noritake, Japan	Base: Bis-GMA* (1-10%), TEGDMA** (1-10%), HEMA*** (1-13%), 10- MDP****, Sodium Fluoride <1%, LCSi Monomer, radiopaque filler, Silanated Colloidal Silica, Aluminum Oxide Filler, pigments. Catalyst paste: Camphorquinone, Peroxide, Accelerators, Catalysts, Sodium Fluoride.	I
RelyX™ Ultimate	Adhesive resin cement	3M ESPE, St. Paul, MN, USA	Base: Methacrylate monomers, radiopaque silanated fillers, initiator components, stabilizers and rheological additives. Catalyst Paste: Methacrylate monomers, radiopaque alkaline (basic) fillers, initiator components, stabilizers, pigments, rheological additives, fluorescence dye, dark cure activator for Scotchbond Universal adhesive.	II
Panavia™ V5	Adhesive resin cement	Kuraray Noritake Dental Inc; Tokyo, Japan	Base: Bis-GMA* (5-15%), TEGDMA**<5%, 10- MDP****, Hydrophobic Aromatic Dimethacrylate, Hydrophilic Aliphatic Dimethacrylate, Silanated Barium Glass Filler, Silanated Fluoroaluminosilicate Glass Filler, Colloidal Silica, Surface-Treated Aluminum Oxide Filler, Initiators and Accelerators, Pigments. Catalyst paste: Bis-GMA*, Camphorquinone, Hydrophilic Aliphatic Dimethacrylate, Silanated Barium Glass Filler, Silanated Aluminum Oxide Filler,Colloidal Silica, Accelerators, Catalysts, Pigments.	II

* Bis-GMA: Bisphenol-A-glycidyl dimethacrylate.
** TEGDMA: Triethylene glycol dimethacrylate.
***HEMA: 2-Hydroxyethyl Methacrylate.
**** 10-MDP: 10-Methacryloyloxydecyl Dihydrogen Phosphate.

4.2 Methods

4.2.1 Preparation of Test Specimens

4.2.1.1 Fabrication of Test Specimens and Teeth Selection (Study I, and II)

Forty freshly extracted, sound human premolars free of caries, cracks, and restorations were selected (n = 10 per group). After the mechanical debridement of soft tissues using a hand scaler, the specimens were stored in saline at 37°C to maintain hydration. Each tooth was embedded in self-curing acrylic resin (VariDur, Buehler) with the crown portion exposed for standardized preparation. All teeth were prepared by a single calibrated operator (S.S.) using a high-speed electric handpiece (EVO.15 1:5 L MicroSeries, Bien Air) with continuous air-water cooling and diamond burs (847KR, Komet USA). Tooth preparations included a 1 mm axial shoulder margin with a rounded configuration and an occlusal reduction of 1.2 mm for zirconia crowns and 1.5 mm for lithium disilicate. The convergence angle ranged between 6° and 10° to ensure passive crown seating.

4.2.1.2 Computer-Aided Design and Manufacturing of Experimental Ceramic Crowns (Study I, and II)

All prepared teeth were scanned using an intraoral scanner (TRIOS 4; 3Shape A/S, Copenhagen, Denmark). The digital scan files were exported to MeshMixer software (Autodesk Inc., San Rafael, CA, USA) for the calculation of prepared tooth surface area (mm^2) and estimated cement volume (mm^3). Crowns were virtually designed using CAD software (3Shape Dental System 2020; 3Shape A/S, Copenhagen, Denmark) with a uniform 1 mm margin width, 1.2–1.5 mm occlusal thickness, and a cement space of 40 µm. Crowns were milled using a 5-axis milling machine (PrograMill PM7; Ivoclar Vivadent, Schaan, Liechtenstein) from pre-sintered zirconia discs (3 mol%, 4 mol%, and 5 mol% Y-TZP) and lithium disilicate ceramic blocks (IPS e.max CAD™; Ivoclar Vivadent). Zirconia crowns were subsequently sintered, while lithium disilicate crowns were crystallized, followed by staining and glazing in accordance with the respective manufacturers' instructions.

All crowns were evaluated for marginal fit and adaptation on the corresponding prepared teeth. The intaglio surfaces of the zirconia crowns were conditioned by air-particle abrasion using 50 µm aluminum oxide particles at a pressure of 30 pounds per square inch (PSI) for 15 s, maintaining a nozzle distance of 10 mm.

4.2.1.3 Cementation Protocol (Study I)

Crowns were seated under manual pressure and luted using Panavia™ SA Universal (Kuraray Noritake, Japan) following the manufacturer's instructions. Excess cement was removed after a 5-s tack cure using a polymerization light (Valo, Ultradent Products Inc., Utah, USA), with an irradiance of 800–1200 mW/cm² on the facial and lingual surfaces. Final curing was performed for 20 s on buccal, lingual, and occlusal aspects. Cemented specimens were stored in a humidor at 37°C until further testing.

4.2.1.4 Experimental Groups and Cementation (Study II)

The same tooth preparation and digital scanning protocol described in Study I was employed for Study II. Two groups of monolithic ceramic crowns were fabricated (n = 20 per group):

- Group 1 (G1): 3Y-PSZ zirconia crowns (Katana™ HT; Kuraray Noritake Dental Inc., Japan)
- Group 2 (G2): lithium disilicate glass ceramic crowns (IPS e.max CAD™; Ivoclar Vivadent, Liechtenstein)

Both groups were subdivided based on the cementation protocol:

G1a / G2a: Panavia SA (Universal, Kuraray Noritake, Jaban), a two-step adhesive resin cement. For G1a, zirconia crowns were air-particle abraded and primed; for G2a, lithium disilicate crowns were etched with 5% hydrofluoric acid for 20 s.

G1b / G2b: RelyX™ Ultimate (3M ESPE, Oral Care, St. Paul, MN, USA), a one-step adhesive cement with Scotchbond Universal (3M ESPE, Oral Care, St. Paul, MN, USA) applied to the internal crown surface. Crowns were seated manually. Excess cement was removed after 2 s of tack curing with a Valo curing light with an irradiance value of 1180 mW/cm^2 (Valo, Ultradent Products Inc., Utah, USA), applied to the facial and lingual aspects. This was followed by 20 s of final curing on buccal, lingual, and occlusal surfaces. All specimens were stored in distilled water at 37°C for 24 hours prior to the debonding procedure.

4.2.1.5 Preparation of Disc-Shaped Specimens for Optical Properties and Mechanical Properties Measurements (Study III)

A total of 40 disc-shaped specimens (n = 10 per group) were fabricated, each with a diameter of 14 mm and a thickness of 1.2 mm. Specimens were milled using a 5-axis milling machine (PrograMill PM7; Ivoclar Vivadent, Liechtenstein) from the following ceramic materials:

- Group 1 (G1): 3Y-TZP (Katana™ HTML; Kuraray Noritake Dental Inc., Japan)
- Group 2 (G2): 4Y-TZP (Katana™ STML; Kuraray Noritake Dental Inc., Japan)
- Group 3 (G3): 5Y-TZP (Katana™ UTML; Kuraray Noritake Dental Inc., Japan)
- Group 4 (G4): Lithium disilicate ceramic (IPS e.max CAD™; Ivoclar Vivadent, Liechtenstein)

Zirconia discs were sintered in a high-temperature furnace following the manufacturer's recommended sintering program (Programat S1; Ivoclar Vivadent, Schaan, Liechtenstein), while lithium disilicate crowns were crystallized, followed by staining and glazing according to the respective manufacturers' instructions. After sintering, specimens were standardized to a thickness of 1.2 ± 0.05 mm by sequential polishing with silicon carbide papers (#380, #600, #1200; MicroCut, Buehler) under water coolant. Thickness was verified using a digital micrometer (Digimatic Micrometer; Mitutoyo Corp.). Specimens were ultrasonically cleaned in distilled water for 5 min and air-dried for 20 s.

4.2.2 Laser Irradiation Treatment (Studies I–III)

In both Study I and Study II, laser irradiation was performed using an Er:YAG laser device (LightWalker; Fotona™, Ljubljana, Slovenia) operating at a wavelength of 2940 nm. The irradiation parameters were standardized across both studies as follows: pulse energy of 335 mJ, frequency of 15 Hz, average power output of 5.0 W, water/air spray setting of 4/4, and super short pulse (SSP) mode (50 µs). A tipless handpiece (HO2; Fotona™) was used, and laser application was carried out at a distance of 5–8 mm with the beam directed perpendicularly to the crown surface. The selected parameters were based on previous literature and manufacturer recommendations. Irradiation was performed by a single calibrated operator using continuous sweeping motion at a constant distance. In Study I, all crown surfaces (buccal, lingual, mesial, distal, and occlusal) were evenly irradiated. In Study II, axial motion was restricted to the buccal and lingual surfaces to simulate limited clinical access to interproximal areas. During irradiation, air-water spray cooling was maintained to prevent thermal damage. A visible darkening of the underlying cement was observed, indicating cement degradation and disruption of the adhesive interface.

4.2.3 Debonding Procedure and Irradiation Time Assessment (Study I, and II)

In both Study I and Study II, the debonding of all-ceramic crowns was assessed following standardized laser irradiation protocols. Laser energy was applied sequentially to all accessible surfaces of the crown. After the initial irradiation cycle, crown mobility was evaluated using gentle manual and mechanical techniques. These included finger-pulling actions, digital manipulation, and light elevating forces. If necessary, a crown removal instrument (Crown Remover Plier; Henry Schein, USA) was employed to assist dislodgement by engaging the buccal and lingual marginal openings. Debonding was considered successful when the crown could be passively removed without fracture or the use of excessive force, indicating the loss of adhesive integrity at the tooth-cement interface. If the crown remained bonded, additional irradiation intervals followed by repeated dislodgement attempts were performed until successful retrieval. For each specimen, the total irradiation time (in min) required to achieve complete debonding was recorded. This measurement served as the primary outcome variable for evaluating the efficiency of laser-assisted crown removal across different experimental conditions.

4.2.4 Optical Property Measurements (Study III)

Color difference (ΔE_{00}) and translucency parameter (TP) were measured using a reflection spectrophotometer (CI7600 X-rite, Grand Rapids, Michigan, USA). The CIE L (lightness), C (chroma), and H (hue) values were determined over a white background using the CIE D65 illuminant and the CIE 2° standard colorimetric observer (as defined by the International Commission on Illumination). The chroma (C*) and hue angle (H*) values were calculated by the spectrophotometer software from the measured a* and b* coordinates, where $C^* = (a^{*2} + b^{*2})^{1/2}$ and $H^* = \arctan(b^*/a^*)$.

Each specimen was calculated according to the CIEDE2000 formula (ΔE_{00}):

$$\Delta E_{00} = \sqrt{\left(\frac{\Delta L'}{k_L S_L}\right)^2 + \left(\frac{\Delta C'}{k_c S_c}\right)^2 + \left(\frac{\Delta H'}{k_H S_H}\right)^2 + R_T \frac{\Delta C'}{k_C S_C} \frac{\Delta H'}{k_H S_H}} \qquad (1)$$

where $\Delta L'$, $\Delta C'$, and $\Delta H'$ represent the differences in lightness, chroma, and hue, respectively, and k_L, k_C, and k_H are parametric correction factors, which were set to 1 in the present study.

TP was calculated using the equation:

$$TP = [(Lb^* - Lw^*)^2 + (ab^* - aw^*)^2 + (bb^* - bw^*)2]^{1/2} \qquad (2)$$

Spectrophotometer calibration was performed before each measurement.

4.2.5 Biaxial Flexural Strength Measurements (Study III)

Biaxial flexural strength was measured using a universal testing machine (Instron™ 4411, Instron™ Corp., USA), in accordance with the ISO Standard 6872. Each ceramic specimen was placed on a support fixture consisting of three symmetrically arranged stainless steel balls (diameter: 4.5 ± 2 mm), positioned 120° apart to form a support circle of 11 ± 1 mm in diameter.

A steel loading piston (diameter: 1.4 ± 0.2 mm) applied a central load perpendicular to the specimen surface at a crosshead speed of 1 mm/min until fracture occurred. The fracture load (P, in newtons) was recorded using the accompanying software (Bluehill, Instron Corp.).

The biaxial flexural strength was calculated according to the following *formula*:

$$\mathrm{S} = -0.2387\mathrm{P}(\mathrm{X} - \mathrm{Y})/\mathrm{d}^2 \tag{3}$$

where S=biaxial flexural strength (MPa); P=fracture load (N); d=specimen disk thickness at fracture origin (mm); $X=(1+n)\ \ln\ (B/C)^2+[(1\text{-}n)/2](B/C)^2$; $Y=(1+n)\ln\ (A/C)^2+[(1\text{-}n)/^2](A/C)^2$, where ν=Poisson coefficient (ceramic=0.25, ISO 6872); A=radius of support circle (mm); B=radius of loaded area (mm); and C=radius of specimen disk (mm).

4.2.6 Surface Roughness Measurement (Study III)

Surface roughness (R_a) was evaluated using a confocal laser scanning microscope (VK-X1000, Keyence Corp., Japan) at 5× magnification. Each specimen was scanned before and after laser treatment to determine arithmetic mean surface roughness (R_a) by measuring peaks and valleys along two roughness profiles (one in the long axis and one perpendicular to the long axis) along the surface of the specimen. Prior to scanning, specimens were gently rinsed with water and cleaned with soft, anti-static, lint-free wipes (Kimwipes, Kimtech Science) to prevent contamination. The arithmetic mean surface roughness (R_a) was calculated according to ISO 21920 standards using the formula:

$$Ra = \frac{1}{\ell r}\int_0^{\ell r} |Z(x)\ |dx \tag{4}$$

R_a=Arithmetic means roughness, ℓr=reference length, $Z(x)$=the dimensionless fourth power of the reference length.

4.2.7 Scanning Electron Microscopy (SEM)

Following successful Er:YAG laser debonding treatment in both Study I and Study II, the internal surfaces of the retrieved crowns were examined to evaluate surface integrity and characterize the mode of adhesive failure. A field emission scanning electron microscope (FE-SEM; Hitachi S-4700, Hitachi High Technologies Co., Tokyo, Japan) was used for high-resolution surface imaging.

Specimens were sputter-coated with a thin layer of gold-palladium prior to imaging. The FE-SEM analysis allowed for detailed visualization of the cement remnants, fracture patterns, and morphological alterations on the fitting surfaces of the ceramic crowns. The failure mode was classified as adhesive (at the cement-restoration interface), cohesive (within the cement), or mixed, based on SEM observations. These assessments were conducted to determine the extent of laser-induced changes and the quality of the debonding interface, contributing to the evaluation of the safety and efficacy of erbium laser use in crown retrieval.

4.3 Statistical Analysis

In Study I, statistical analysis was performed using one-way analysis of variance (ANOVA) to evaluate differences in laser-assisted crown debonding times across experimental groups. When significant differences were found, *post hoc* comparisons were conducted using the Tukey Honestly Significant Difference (HSD) test. The significance level was set at $\alpha = 0.05$. Similarly, in Study II, irradiation times required for crown removal were analyzed using one-way ANOVA. *Post hoc* analysis was also conducted using the Tukey HSD test to identify statistically significant pairwise differences among groups, with a confidence level of 95% ($p < 0.05$). In Study III, data distribution was first assessed using the Kolmogorov–Smirnov test. Non-normally distributed variables (L*, C*, and H* values) were analyzed using non-parametric tests, including the Kruskal–Wallis and Mann–Whitney U tests ($p = 0.05$). Variables that followed normal distribution, namely color difference (ΔE_{00}), translucency parameter (TP), contrast ratio (CR), surface roughness (R_a), and biaxial flexural strength, were analyzed using one-way ANOVA. Bonferroni *post hoc* tests were applied for multiple comparisons ($p= 0.05$). Additionally, the Spearman correlation test was used to assess the correlations between material properties and laser parameters ($p < 0.05$). All statistical analyses were performed using statistical software (Version 25.0; SPSS. Inc., Chicago, Illinois), and significance was defined at $p \leq 0.05$ throughout.

5 Results

5.1 Influence of Zirconia Composition on Er:YAG Laser-Assisted Debonding of Crowns (Study I)

Table 4 summarizes the mean and standard deviation of crown retrieval in min for all tested groups. All the crowns were successfully retrieved using Er:YAG laser irradiation without causing structural damage to the supporting teeth. However, one lithium disilicate crown exhibited a fracture during manual retrieval, possibly due to torsional stress. The average debonding time varied significantly across ceramic types. Crowns fabricated from 3 mol% and 4 mol% yttria-stabilized tetragonal zirconia polycrystals (3Y-TZP and 4Y-TZP) required longer irradiation times (12.46 ± 4.17 min and 10.30 ± 3.33 min, respectively) compared to those made from 5Y-TZP (4.03 ± 1.61 min) and lithium disilicate (2.08 ± 0.92 min). Statistical analysis showed that the differences were significant ($P < 0.05$), except between 3Y-TZP and 4Y-TZP ($P = 0.218$) and between 5Y-TZP and lithium disilicate ($P = 0.423$). The average surface areas of the prepared teeth were as follows: 109.9 ± 10.0 mm² for the 3 mol% Y-TZP group, 107.5 ± 13.6 mm² for the 4 mol% Y-TZP group, 109.5 ± 13.1 mm² for the 5 mol% Y-TZP group, and 83.4 ± 8.9 mm² for the lithium disilicate group. No statistically significant differences were found among the zirconia groups ($P > .05$).

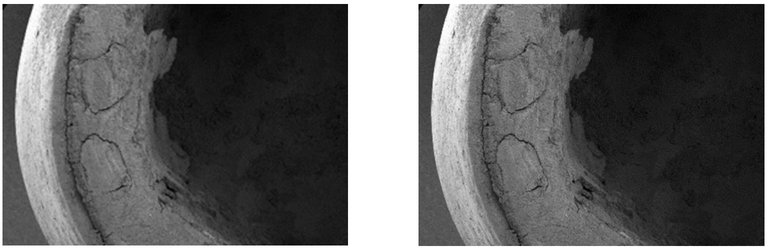
Table 4. Mean and standard deviation (SD) of the crown retrieval in min of all groups.

Ceramic type	**Crown Retrieval Time (min) (Mean ±SD)**	**P Value**
3 mol% Y-TZP	12.46 ± 4.17^a	0.218
4 mol% Y-TZP	10.30 ± 3.33^a	
5 mol% Y-TZP	4.03 ± 1.61^b	0.423
Lithium Disilicate	2.08 ± 0.92^b	

Same superscript letter indicates no statistical significance (P>0.05)

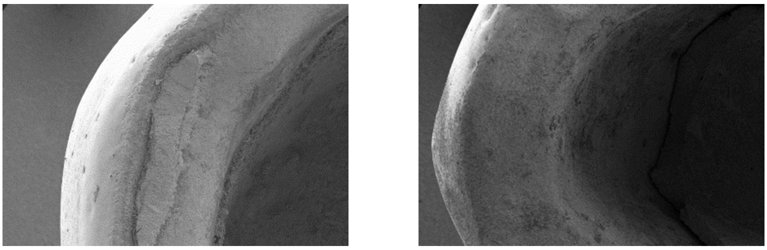
5.2 Scanning Electron Microscopy (Study I)

Evaluation under scanning electron microscopy (SEM) revealed no signs of structural damage indicative of thermal degradation or photoablation. Both ceramic and tooth surfaces showed no evidence of carbonization, cracks, or mechanical failure, except for the previously noted fractured crown. Predominantly adhesive failure was observed, with residual cement primarily localized on the internal surface of the crowns as shown in Figure 1. Partial cement ablation and signs of laser-induced micro-explosive activity were occasionally noted at the bonding interface. The SEM image in Figure 2 shows that the dentin surfaces of the abutment teeth retained an intact smear layer with scattered remnants of cement following laser-assisted retrieval.



(A) 3 mol% Y-TZP zirconia

(B) 4 mol% Y-TZP zirconia



(C) 5 mol% Y-TZP zirconia

(D) lithium disilicate

Figure 1. Scanning electron microscopy (SEM) images (original magnification 35×) of the internal surfaces of ceramic crowns after Er:YAG laser irradiation. The images correspond to the following materials: **(A)** 3 mol% Y-TZP zirconia, **(B)** 4 mol% Y-TZP zirconia, **(C)** 5 mol% Y-TZP zirconia, and **(D)** lithium disilicate.

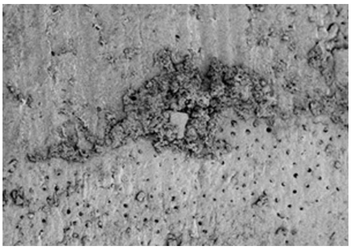


Figure 2. SEM image (original magnification 500×) of the tooth surface after Er:YAG laser application, illustrating the smear layer and remnants of luting cement.

5.3 Influence of Adhesive Resin Cement Type on Crown Debonding Efficiency (Study II)

In this study, two-bottle (Panavia™ V5) and one-bottle (RelyX™ Ultimate) adhesive resin cements were assessed for their effect on crown debonding using Er:YAG laser irradiation. Table 5 summarizes the mean and standard deviation of crown debonding in min for all tested groups.

All crowns were successfully retrieved without any damage to either the ceramic restoration or the tooth structure. For zirconia crowns (3Y-PSZ), the mean time needed for debonding was 5.75 ± 2.00 min for the G1a with group and 4.79 ± 1.20 min for the G1b group. Lithium disilicate crowns debonded more rapidly, with average times of 1.69 ± 0.49 min and 1.12 ± 0.17 min for G2a and G2b, respectively.

There was no significant difference between the adhesive types within the same ceramic group ($P > 0.05$). However, comparisons across ceramic types revealed significantly faster debonding times for lithium disilicate ($P < 0.05$).

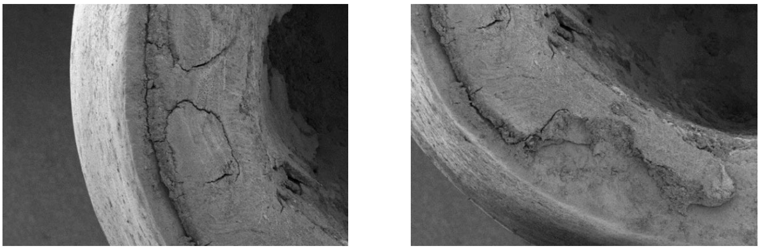
Table 5. Mean and standard deviation (SD) of the crown debonding in min of all groups bonded with two-bottle (Panavia™ V5) and one-bottle (RelyX™ Ultimate) adhesive resin cements.

Ceramic/ Cement Type	**Crown Debonding Time (Mean ±SD)**	**P Value**
3Y-PSZ/ Panavia™ V5 (G1a)	5.75 ± 2.00^{a}	0.2914
3Y-PSZ/ RelyX™ Ultimate (G1b)	4.79 ± 1.20^{a}	
Lithium Disilicate/ Panavia™ V5 (G2a)	1.69 ± 0.49^{b}	0.7116
Lithium Disilicate/ RelyX™ Ultimate (G2b)	1.12 ± 0.17^{b}	

Same superscript letter indicates no statistical significance ($P>0.05$)

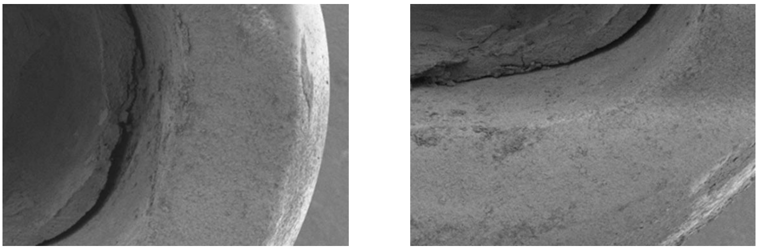
5.4 Scanning Electron Microscopy (Study II)

Visual assessment and scanning electron microscopy (SEM) analysis revealed no structural deterioration or thermal damage suggestive of laser-induced photoablation on any of the retrieved restorations or underlying tooth surfaces (Figure 3). Predominantly adhesive failures were observed at the crown-tooth interface, with residual cement frequently identified on the intaglio surface of the debonded crowns. No evidence of carbonization, surface cracks, or microstructural defects was detected. In some cases, localized disruption of the cement layer, attributed to laser interaction, was observed. SEM evaluation of the crown/cement interface further demonstrated cement alterations, including ablation zones, cement explosion, and hydrodynamic ejection features consistent with laser-induced effects (Figure 4).



(A) 3Y-PSZ zirconia crown bonded with Panavia V5

(B) 3Y-PSZ zirconia crown bonded with RelyX ultimate



(C) Lithium disilicate crown bonded with Panavia V5

(D) Lithium disilicate crown bonded with RelyX ultimate

Figure 3. SEM images (original magnification ×50) showing the internal surfaces of ceramic crowns after exposure to Er:YAG laser irradiation. The images represent different combinations of restorative material and adhesive resin cement: 3Y-PSZ zirconia with Panavia™ V5, 3Y-PSZ zirconia with RelyX™ Ultimate, lithium disilicate with Panavia™ V5, and lithium disilicate with RelyX™ Ultimate. Distinct surface morphology and cement interaction can be observed across the different material combinations.

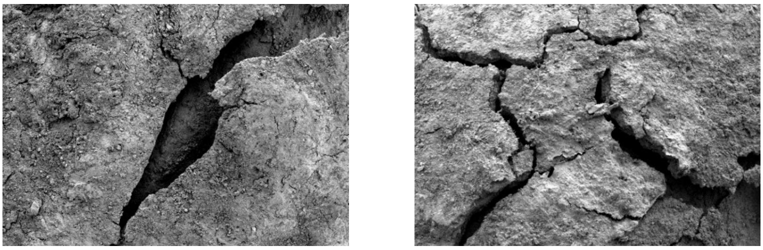


Figure 4. SEM images (original magnification ×100) illustrating morphological alterations at the crown–cement interface following Er:YAG laser application, including features suggestive of cement disruption and thermal ejection phenomena.

5.5 Biaxial Flexural Strength (Study III)

Table 6 presents the biaxial flexural strength values. After laser irradiation, significant increases were observed in G3 and G4) ($P < 0.05$). G1 and G2 did not exhibit significant changes in mechanical strength following laser irradiation ($P > 0.05$).

Table 6. Mean and standard deviation of biaxial flexural strength (MPa) of all groups before and after Er:YAG laser irradiation.

Ceramic type	Before Laser Irradiation Biaxial Flexural Strength MPa (Mean ± SD)	After Laser Irradiation Biaxial Flexural Strength MPa (Mean ± SD)	P Value
3Y-PSZ Zirconia (G1)	985.91 ± 44.15^{a}	983.30 ± 74.29^{a}	1.0002
4Y-PSZ Zirconia (G2)	622.12 ± 65.88^{a}	629.50 ± 78.78^{a}	1.0000
5Y-PSZ Zirconia (G3)	377.57 ± 24.94^{a}	502.92 ± 96.64^{b}	0.0007
Lithium disilicate glass ceramic /Control (G4)	338.50 ± 11.96^{a}	430.76 ± 54.81^{b}	0.0302

Same superscript letter indicates no statistical significance ($P>0.05$).

5.6 Optical Properties (Study III)

5.6.1 Color Change (ΔE_{00})

The mean color difference values (ΔE_{00}) for the four tested groups are summarized in Table 7. Statistically significant differences in ΔE_{00} were found between G1 and G2 ($P = 0.0010$), G1 and G3 ($P = 0.0001$), and G1 and G4 ($P < 0.0001$). Only G1 exhibited a ΔE_{00} value below the clinically acceptable threshold of 1.8, while all other groups (G2–G4) exceeded this threshold, indicating perceptible color changes following Er:YAG laser irradiation.

Table 7. Mean and standard deviation of color difference (ΔE_{00}) values following Er:YAG laser irradiation of all tested groups.

Ceramic type	Color Change ΔE_{00} (Mean ± SD)
3Y-PSZ Zirconia (G1)	$1.22 \pm 0.38^{a*}$
4Y-PSZ Zirconia (G2)	$2.37 \pm 0.75^{b**}$
5Y-PSZ Zirconia (G3)	$2.63 \pm 0.86^{b**}$
Lithium disilicate glass ceramic/Control (G4)	$2.67 \pm 0.24^{b**}$

Same superscript letter indicates no statistical significance ($P>0.05$)

* ΔE_{00} is below the acceptability threshold of 1.8.

** ΔE_{00} is above the acceptability threshold of 1.8.

5.6.2 Translucency Parameter (TP)

The TP values before and after laser treatment are presented in Table 8. A statistically significant increase in translucency was observed only in G4 after Er:YAG irradiation (P = 0.0001). The change in G4 exceeded the defined translucency acceptability threshold of 2.6.

No significant differences were detected in G1, G2, or G3.

Table 8. Mean and standard deviation of translucency parameter (TP) of all groups before and after Er:YAG laser irradiation.

Ceramic type	Before Laser Irradiation Translucency Parameter (Mean ± SD)	After Laser Irradiation Translucency Parameter (Mean ± SD)	P Value
3Y-PSZ Zirconia (G1)	6.37 ± 1.75^{a}	7.10 ± 0.78^{a}	0.9423
4Y-PSZ Zirconia (G2)	6.42 ± 1.98^{a}	7.56 ± 1.5^{a}	0.6229
5Y-PSZ Zirconia (G3)	8.23 ± 0.74^{a}	6.71 ± 1.10^{a}	0.2514
Lithium disilicate glass ceramic /Control (G4)	8.46 ± 1.41^{a}	$13.96 \pm 1.52^{b*}$	0.0001

Same superscript letter indicates no statistical significance (P>0.05)
*Change in translucency is beyond the acceptability threshold of 2.6.

5.7 Surface Roughness (Study III)

The surface roughness (R_a) values before and after laser treatment are presented in Table 9. Surface roughness remained stable across all groups before and after laser irradiation. No statistically significant differences were observed in R_a values ($P > 0.05$).

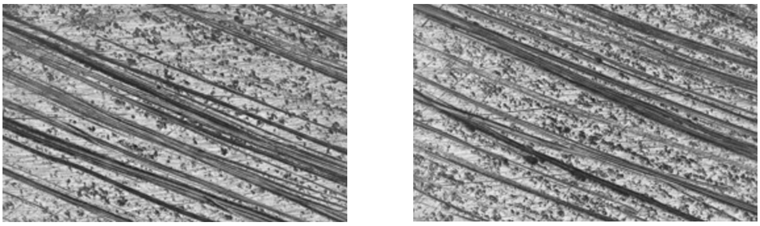
Table 9. Mean and standard deviation of surface roughness (R_a) of all groups before and after Er:YAG laser irradiation.

Ceramic type	Before Laser Irradiation Surface Roughness (Mean ± SD)	After Laser Irradiation Surface Roughness (Mean ± SD)	P Value
3Y-PSZ Zirconia (G1)	1.39 ± 0.18a	1.25 ± 0.27a	0.9706
4Y-PSZ Zirconia (G2)	1.29 ± 0.18^{a}	1.30 ± 0.17^{a}	1.0002
5Y-PSZ Zirconia (G3)	0.96 ± 0.32^{a}	0.93 ± 0.32^{a}	1.0000
Lithium disilicate glass ceramic /Control (G4)	1.34 ± 0.48^{a}	1.29 ± 0.36^{a}	1.0000

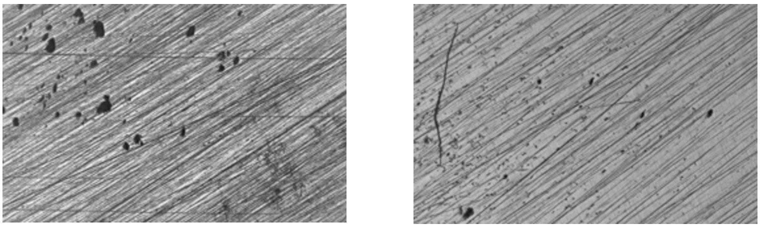
Same superscript letter indicates no statistical significance (P>0.05).

5.8 Scanning Electron Microscopy (Study III)

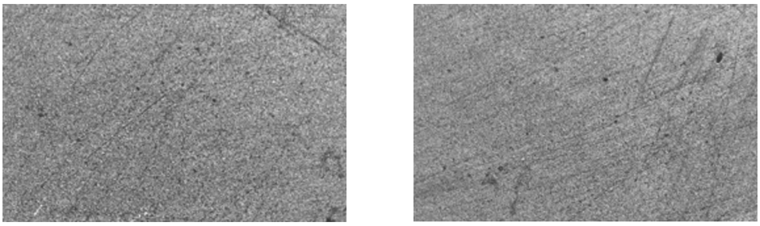
Scanning electron microscopy (SEM) analysis demonstrated no visually apparent alterations in the microstructure of any of the tested materials following Er:YAG laser irradiation. These observations were consistent across all groups, indicating that the laser parameters used did not produce detectable changes in surface topography or roughness under SEM evaluation, as shown in Figure 5.



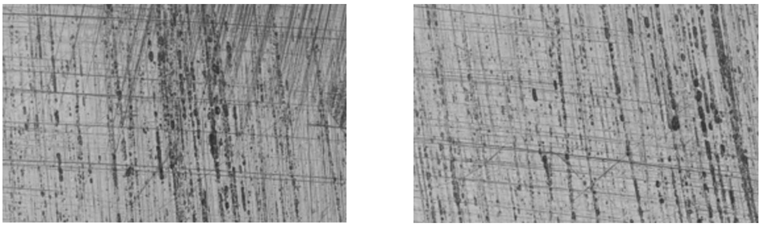
(A) 3Y-PSZ zirconia before laser **(A)** 3Y-PSZ zirconia after laser



(B) 4Y-PSZ zirconia before laser **(B)** 4Y-PSZ zirconia after laser



(C) 5Y-PSZ zirconia before laser **(C)** 5Y-PSZ zirconia after laser



(D) IPS e.max before laser **(D)** IPS e.max after laser

Figure 5. SEM images showing surface characteristics of ceramic specimens before and after Er:YAG laser irradiation. The images illustrate **(A)** 3Y-PSZ Zirconia (×2000, 20 µm), **(B)** 4Y-PSZ Zirconia (×2000, 20 µm), **(C)** 5Y-PSZ Zirconia (×5000, 20 µm), and **(D)** IPS e.max (×2000, 50 µm).

6 Discussion

6.1 General Discussion

This PhD thesis presents a comprehensive investigation of Er:YAG laser-assisted debonding of contemporary ceramic restorations, specifically evaluating three core aspects: the influence of ceramic type (zirconia *vs*. lithium disilicate glass ceramics), the role of resin cement systems (2-bottle *vs*. 1-bottle adhesives), and the changes in optical and mechanical properties following laser exposure. All experimental designs were methodologically aligned to simulate real-world clinical workflows using CAD/CAM-fabricated crowns and standardized Er:YAG laser parameters (335 mJ; 15 Hz; 5.0 W) to ensure consistency and translational relevance. The chosen parameters were based on those established in earlier studies to avoid thermal pulpal injury while achieving efficient debonding. (Zach & Cohen, 1965; Rechmann *et al.*2014; Downarowicz *et al.*2020).

This comprehensive approach was motivated by the increasing demand for minimally invasive dentistry, where preservation of healthy tooth structure and existing restorations is prioritized. Traditional methods of crown removal using rotary instruments are often invasive, and time-consuming, and risk damaging both the restoration and the abutment. The use of Er:YAG laser technology provides a novel alternative, facilitating targeted ablation of the luting cement while maintaining the integrity of the restoration and the underlying tooth structure. This research is timely and significant as the prevalence of all-ceramic restorations continues to rise in response to the demand for esthetic, durable, and metal-free restorative options.

Study I aimed to determine how yttria content in zirconia affects laser debonding efficiency. Specifically, it compared the Er:YAG laser debonding times for 3Y-TZP, 4Y-TZP, and 5Y-TZP zirconia crowns, along with lithium disilicate crowns (IPS E.max) as the control group. The underlying hypothesis was that laser debonding time would be independent of the ceramic type.

Study II focused on whether the resin cement system influences debonding time. It compared Panavia$^{\text{TM}}$ V5 (2-bottle) and RelyX™ Ultimate (1-bottle) adhesives with zirconia and lithium disilicate crowns to test whether cement composition affects laser interaction and ablation time.

Study III examined whether the same Er:YAG laser settings used for debonding affect the optical and mechanical properties of ceramics. This addresses the clinical viability of restoration reuse following debonding.

By structuring the investigation across three distinct studies, the thesis ensures a clear delineation of each contributing factor material type, cement system, and irradiation effect while maintaining coherence and consistency across the research questions. The laser parameters used were kept constant to isolate the effects of these individual variables. The outcomes of these studies collectively contribute to the development of guidelines for clinical application and material selection when considering laser-assisted restoration retrieval. The expanded sections below provide a detailed analysis of each study's findings and their broader implications.

In relation to the original hypotheses proposed in this thesis, the findings allow their evaluation. The first hypothesis, that Er:YAG laser-assisted retrieval can be performed without compromising the structural integrity of ceramic restorations, was largely supported by the results of Study III, which demonstrated no detrimental effects on mechanical strength or surface integrity. The second hypothesis, stating that the type of luting cement does not influence laser retrieval efficiency, was accepted, as no significant differences in debonding time were observed between the tested resin cement systems. The third hypothesis, that laser irradiation does not significantly affect the optical properties of ceramic materials, was partially accepted, since some materials exhibited measurable color changes, although these changes remained within clinically acceptable limits in most cases.

6.2 Debonding Efficiency and Ceramic Type (Study I)

The first study focused on comparing the debonding efficiency of lithium disilicate with three types of zirconia differing in yttria content: 3Y-TZP, 4Y-TZP, and 5Y-TZP zirconia, and lithium disilicate. These materials were selected based on their distinct microstructural characteristics and clinical popularity. The null hypothesis of the study was rejected. The results showed a clear inverse relationship between yttria content and debonding time. Crowns fabricated from 3Y-TZP, characterized by low translucency and high tetragonal phase content, required the longest irradiation time (mean ≈ 12.5 min), followed by 4Y-TZP (≈ 10.3 min), 5Y-TZP (≈ 4.0 min), and lithium disilicate (≈ 2.0 min), which displayed the shortest debonding time. The fundamental reason is that lithium disilicate ceramic, a glass-ceramic with a relatively low crystalline content, allows greater transmission and absorption of the 2940 nm Er:YAG wavelength compared to the highly crystalline, opaque microstructure of 3Y-TZP zirconia (Sari *et al.*2014). The Er:YAG laser energy is readily absorbed through the lithium disilicate, quickly heating and breaking down the resin cement underneath (Deeb *et al.*2019; Elkharashi *et al.*2020; Al-Juaila *et al.*2018). In contrast, 3Y-TZP zirconia crowns, characterized by their high opacity and low cubic content, exhibited significantly longer debonding times due to limited light penetration and greater scattering of the laser beam (Sulaiman *et al.*2015; Zhang, 2014).

These outcomes reflect the intrinsic differences in optical properties of the tested ceramics. As previously reported by Zhang *et al.*(2014) and Sulaiman *et al.*(2015), the increase in cubic phase content in high-translucency zirconia (particularly in 5Y-TZP) improves laser energy transmission by reducing internal scattering. This higher transmission efficiency allows more energy to reach and ablate the cement layer, accelerating the debonding process. In contrast, the dense, highly crystalline structure of 3Y-TZP zirconia (which consists of ~85–90% tetragonal phase, with low translucency) limits laser energy penetration, resulting in longer debonding durations (Deeb *et al.*2019; Rechmann *et al.*2015; Gozneli *et al.*2019).

With increased yttria content, as in 4Y-TZP (≈75% tetragonal/25% cubic) and 5Y-TZP (which contains ~50% cubic phase and is more translucent), the zirconia material becomes more translucent due to a higher proportion of the cubic phase, facilitating better light transmission and, thus, more efficient cement ablation. The performance of 5Y-TZP approached that of lithium disilicate ceramic, demonstrating that higher-translucency zirconia offers a viable compromise between esthetics, mechanical integrity, and ease of removal (Burgess, 2018; Sulaiman *et al.*2015).

The findings also emphasize the material-specific response to laser energy, demonstrating that ceramics with higher translucency require shorter debonding times. Clinicians should be aware that materials like 5Y-TZP and lithium disilicate glass ceramic offer not only esthetic benefits but also facilitate faster and less invasive retrieval if needed. This has clinical relevance in optimizing treatment plans based on the anticipated need for potential restoration retrieval. Furthermore, using laser parameters that do not damage the ceramic or tooth structure ensures that the crown can potentially be reused, thereby reducing costs and improving efficiency in clinical practice.

It is also important to note that although lithium disilicate ceramic was more favorable in terms of debonding efficiency, its fracture resistance is lower than that of zirconia, especially 3Y-TZP. Therefore, a balance must be struck between ease of retrieval and long-term functional performance. In clinical scenarios involving high occlusal loads, zirconia may still be preferable despite the longer debonding time

The SEM analysis provided additional confirmation of the laser's mode of action, cement ablation through thermal and hydrodynamic effects without observable damage to the ceramic or tooth structure, which is consistent with findings from Morford *et al.*(2011) and Elkharashi *et al.*(2020).These outcomes support the clinical use of Er:YAG lasers for selective and safe crown retrieval and reinforce the importance of selecting ceramics with appropriate optical characteristics when anticipating possible future restoration removal (Deeb *et al.*2019; Deeb *et al.*2020; Deeb *et al.*2022; Grzech-Lesniak *et al.*2018).

6.3 Influence of Resin Cement Type (Study II)

Study II extended the investigation to explore the influence of two adhesive resin cement systems, a 2-bottle system (Panavia^{TM} V5) and a 1-bottle system (RelyX™ Ultimate), on laser debonding efficiency. The purpose was to determine whether differences in cement formulation and bonding protocol would significantly impact the time required to retrieve restorations using standardized laser parameters. The hypothesis was that differences in resin chemistry and adhesive strategy does not affect debonding of different ceramic restorations during Er:YAG laser application.

According to expectations, the results showed that, within each ceramic category, there was no statistically significant difference in debonding times between the crowns bonded with Panavia^{TM} V5 and those bonded with RelyX™ Ultimate. This outcome suggests that, under controlled conditions with consistent ceramic thickness and laser settings, the adhesive resin cement type plays a limited role in influencing the overall efficiency of the laser debonding process compared to the ceramic material when it comes to influencing laser energy transmission. Thus, the type of ceramic plays a significant role in the laser transmission and debonding time, which was consistent with previous studies (Tak *et al.*2014; Morford *et al.*2011; Deeb *et al.*2022; Suliman *et al.*2024).

Additionally, the findings from this study indicated that debonding 3Y-PSZ zirconia crowns, regardless of whether a 1-bottle or 2-bottle adhesive resin cement was used, required approximately three to four times longer than debonding lithium disilicate crowns. Clinically, this suggests that additional chairside time should be anticipated when removing zirconia compared to lithium disilicate restorations. These findings are consistent with previous research (Tak *et al.*2014; Rechmann *et al.*2014; Morford *et al.*2011; Deeb *et al.*2022; Al-Juaila *et al.*2018).

From a clinical perspective, this is a significant finding. It implies that the choice of resin cement can be made based on other clinical considerations such as ease of use, bond strength, post-operative sensitivity, or esthetic properties without compromising the feasibility of future laser-assisted restoration retrieval. However, this conclusion is limited to the resin cements evaluated in the present study, and caution should be exercised when extrapolating these findings to other cement systems with different chemical compositions or bonding mechanisms. SEM analysis of the specimens revealed consistent patterns of cement ablation and intact ceramic surfaces with no signs of thermal damage or microcracking. These observations confirm the previous findings that the Er:YAG laser protocol used in this study is safe and does not negatively impact the structural integrity of the restorations (Morford *et al.*2011; Rechmann *et al.*2015). Additionally, the results reaffirmed the laser's selectivity in targeting the cement interface without damaging the surrounding hard tissue or restoration. This selectivity is essential in conservative dentistry, where preserving the structure of both the restoration and tooth is critical. However, one limitation to consider is the uniformity of ceramic thickness and cementation pressure, which could affect the generalizability of these findings. Also, future studies should investigate whether other cement types, such as self-adhesive or conventional resin cements, show similar responses to laser application.

Overall, this study strengthens the case for using Er:YAG lasers in clinical scenarios with various bonding agents, if laser settings are optimized and material-specific parameters are considered.

6.4 Effects of Er:YAG Laser on Optical and Mechanical Properties (Study III)

Study III addressed a critical question in the clinical adoption of laser-assisted debonding: does Er:YAG laser irradiation compromise the optical or mechanical properties of the ceramic restorations, potentially limiting their reusability. This study evaluated changes in color (ΔE_{00}), translucency (TP), biaxial flexural strength, and surface roughness (R_a) in 3Y-PSZ, 4Y-PSZ, 5Y-PSZ, and lithium disilicate specimens before and after laser exposure.

The color change analysis revealed that all materials, except 3Y-PSZ, exhibited ΔE_{00} values above the clinically acceptable threshold of 1.8 as established by Paravina *et al.* (2015). Lithium disilicate ceramic and the higher yttria containing zirconia groups (4Y- and 5Y-PSZ) showed the greatest color changes. These changes are likely due to thermal alterations in the crystal structure, changes in hydroxyl ion concentration, and redistribution of surface defects (Karaalioğlu and Toksoy, 2010; Paravina *et al.*2015; Zhang *et al.*2024).

The translucency parameter (TP) was significantly increased only in lithium disilicate glass ceramic, suggesting that the laser-induced surface melting and pore reduction enhanced light transmission (Turgut *et al.*2014). For zirconia materials, no significant changes in TP were observed, indicating their optical stability under the tested irradiation conditions (Kurtulmus-Yilmaz *et al.*2019). Meanwhile, no significant change in translucency was observed in the zirconia groups, likely due to their more robust microstructure and lower optical transmission properties (Sulaiman *et al.*2015).

In terms of mechanical properties, both lithium disilicate and 5Y-PSZ showed a significant increase in flexural strength after laser irradiation. This may be attributed to the development of a compressive surface layer formed during localized melting and rapid cooling, like mechanisms observed in laser surface treatment in other ceramic applications (Ahrari *et al.*2014; Kamikura *et al.*2009; Coluzzi *et al.*2010). In contrast, 3Y- and 4Y-PSZ remained mechanically stable, likely due to their inherently stable crystalline structure and limited susceptibility to thermal modification, indicating minimal interaction between the laser and the dense tetragonal matrix. This agrees with the findings of Zhang *et al.* (2021).

Surface roughness (R_a) measurements showed no statistically significant differences before and after laser irradiation across all materials. SEM images confirmed the absence of surface degradation or roughening, indicating that the selected laser settings preserved surface integrity (Gökçe *et al.*2007; Farzin *et al.*2021). This is particularly important in maintaining low plaque accumulation potential and preserving occlusal relationships and antagonist wear properties (Ozdogan and Duymus, 2020; Farzin *et al.*2021).

Collectively, the results suggest that Er:YAG laser application does not compromise and may even enhance some material properties, especially in lithium disilicate and 5Y-PSZ ceramics. This supports their potential for reuse in selected clinical scenarios, reducing both treatment time and material costs.

6.5 Clinical Relevance and Recommendations

The combined findings from the three studies provide a comprehensive and clinically applicable framework for understanding and implementing Er:YAG laser-assisted debonding in restorative dentistry. This technique offers a minimally invasive, efficient, and material-compatible method for ceramic restoration retrieval that preserves both the restoration and the underlying tooth structure.

Key clinical takeaways include the critical role of ceramic type in determining debonding efficiency. Materials with higher translucency, such as lithium disilicate and 5Y-TZP zirconia ceramic, facilitate faster and more predictable laser-assisted removal due to superior optical transmission. Conversely, more opaque ceramics like 3Y-TZP require longer exposure and may pose a greater challenge in retrieval.

Cement type was found to have a negligible effect on debonding efficiency, which allows clinicians to choose resin cements based on their preferences and case-specific requirements without concern for future restoration removal. This finding simplifies treatment planning and supports the broader adoption of laser-assisted techniques across different adhesive protocols.

Importantly, post-irradiation evaluation showed that the Er:YAG laser does not compromise and may even enhance the mechanical strength and translucency of select ceramics. This opens the possibility of reusing retrieved restorations, especially in cases of temporary removal, esthetic modifications, or treatment adjustments. Clinicians should, however, assess each case individually, considering the extent of color change and esthetic demands.

To maximize safety and efficacy, practitioners must adhere to standardized laser parameters, use appropriate cooling strategies, and ensure consistent irradiation techniques to prevent excessive intrapulpal temperature rise. In addition, protective eyewear should be used by both the clinician and the patient, and the laser beam should be applied with controlled movement and intermittent irradiation to avoid localized thermal accumulation. Training and familiarity with laser equipment are essential to prevent unintended thermal damage or inefficient outcomes.

In summary, the results of this thesis support the clinical integration of Er:YAG laser-assisted debonding as a reliable, conservative, and versatile technique in restorative dentistry. By advancing the understanding of material-specific responses to laser irradiation, this research contributes significantly to evidence-based decision-making and the ongoing evolution of minimally invasive dental care.

6.6 Strengths and Weaknesses of the Study

This doctoral thesis encompassed three interrelated studies investigating the use of Er:YAG laser technology for the debonding of lithium disilicate and various zirconia-based restorations. Collectively, these studies present a comprehensive approach to understanding laser-assisted retrieval in restorative dentistry, with specific focus on material type, cement system, and the resulting optical and mechanical changes. While each study addresses distinct research questions, their combined strengths significantly enhance clinical relevance and scientific contribution of the thesis.

One of the principal strengths of this thesis is its systematic and progressive design, where each study builds upon the previous one to provide a holistic perspective.

Study I focused on the influence of ceramic material on laser debonding time, comparing lithium disilicate with three types of zirconia (3Y-TZP, 4Y-TZP, and 5Y-TZP). The primary strength of this study lies in its inclusion of a broad range of commonly used ceramics, allowing for a comparative evaluation of materials with differing translucency and composition. The use of standardized laser parameters and objective retrieval time measurements added methodological robustness. However, a key limitation was its *in vitro* nature, which does not fully replicate intraoral conditions. Also, only one cement type and standardized crown thickness were tested, limiting the generalizability of the results across various clinical settings.

Study II examined the effect of two adhesive resin cement systems (1-bottle and 2-bottle) on debonding times of lithium disilicate and zirconia crowns. Its strength lies in the clinical applicability of testing actual bonded crowns on extracted teeth, closely simulating real-world conditions. The inclusion of SEM analysis provided additional evidence of safe debonding without ceramic or tooth damage. Nonetheless, the study only evaluated two cement systems and used a single crown thickness, which may not reflect the full spectrum of clinical scenarios. Furthermore, the selection of resin cements included in this study (Panavia^{TM} V5 and RelyX™ Ultimate) may represent a limitation, as other resin cements with different chemical compositions or bonding mechanisms may respond differently to laser-assisted debonding. The manual removal force applied during debonding was also unstandardized, potentially introducing variability.

Study III assessed the impact of the Er:YAG laser on the optical (ΔE_{00}, TP) and mechanical (flexural strength, R_a) properties of the same ceramic materials. This study’s strength lies in its detailed and multifactorial analysis of surface and bulk changes after laser irradiation. The integration of flexural testing and SEM imaging enhanced the understanding of how laser energy interacts with ceramic microstructure. A limitation, however, was the absence of follow-up tests simulating re-cementation or functional loading. Moreover, thermal effects on pulp or surrounding tissues were not investigated, which are relevant for complete clinical validation.

Additionally, several limitations related to the laboratory methodology should be acknowledged. All experiments were conducted under controlled *in vitro* conditions using extracted teeth, which cannot fully replicate the complex biological and mechanical environment of the oral cavity. Factors such as saliva, intraoral humidity, thermal fluctuations, and masticatory loading were not simulated and may influence the clinical performance of laser-assisted debonding. Furthermore, the use of standardized crown geometry and thickness in the experimental setup may not fully represent the variability encountered in clinical restorations.

In summary, the trilogy of studies presented in this thesis offers a significant contribution to the field of laser-assisted dentistry, particularly in the context of ceramic restoration retrieval. The comprehensive design, robust methodology, and clinical relevance of the research provide a solid foundation for future investigation and potential clinical adoption. Nevertheless, addressing the outlined limitations through follow-up *in vivo* studies and broader material testing will be essential to fully realize the translational potential of these findings.

6.7 Future Studies and Research Directions

The outcomes of the three studies conducted in this PhD thesis offer promising insights into the clinical potential of Er:YAG laser-assisted debonding of contemporary ceramic restorations. However, further research is warranted to address existing gaps, enhance clinical translation, and optimize protocols for broader use. Future studies should focus on clinical validation through *in vivo* trials. Although the present studies were conducted *in vitro*, clinical trials are necessary to confirm safety and efficacy in real-world conditions, including patient comfort, pulpal health, and operative outcomes. There is a need to evaluate the clinical reusability of debonded restorations. Study III showed preservation of mechanical and optical properties, but further research should assess bonding strength and marginal adaptation after re-cementation, particularly under thermomechanical aging. Expanding the scope of materials and luting agents is another critical direction. Only two resin cements were studied; future research should include a variety of adhesive and self-adhesive systems, as well as additional ceramic types such as feldspathic, hybrid, or multilayered ceramics. Standardization of the removal technique is essential. The tapping force in this study was manually applied. Future work should utilize mechanical debonding devices or digital sensors to minimize operator-dependent variability and enhance reproducibility. Research should also evaluate the influence of restoration geometry and thickness variations. Since real-world restorations vary greatly in design, it is important to understand how laser interaction changes with internal contours or increased material mass. Further investigations into the biological response are warranted. Histological analysis and temperature monitoring during laser exposure would provide essential data on pulpal and periodontal safety, especially in young or thin dentin. Emerging technologies such as predictive modeling and artificial intelligence could optimize laser settings. Data-driven algorithms based on material properties and clinical parameters could enable more personalized and efficient treatment protocols. Finally, studies exploring the environmental and economic impact of laser-assisted debonding would provide valuable insight. The possibility of reusing restorations offers benefits in reducing clinical waste and lowering overall treatment costs. Together, these future directions build upon the solid foundation laid by this thesis and aim to further enhance the application, reliability, and clinical adoption of Er:YAG laser technology in restorative dentistry.

7 Conclusions

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

1. Er:YAG laser-assisted debonding is a safe, efficient, and non-invasive technique for the removal of zirconia and lithium disilicate ceramic restorations. The debonding efficiency is significantly influenced by the type of ceramic material, particularly its yttria content and inherent optical properties. Higher yttria-containing zirconia (e.g., 5Y-TZP) and lithium disilicate, due to their increased translucency, exhibit shorter debonding times compared to opaque ceramics such as 3Y-TZP.
2. The type of adhesive resin cement, whether a 2-bottle or 1-bottle system, does not significantly affect debonding time within the same ceramic material group, indicating that cement composition plays a lesser role compared to ceramic translucency in determining laser energy transmission and debonding performance.
3. Er:YAG laser irradiation influence the optical and mechanical properties of high-translucency ceramics. A notable increase in translucency is seen in lithium disilicate glass ceramic after laser irradiation.
4. Er:YAG laser irradiation increase flexural strength of 5Y-TZP zirconia and lithium disilicate ceramics.
5. Laser-assisted debonding can be performed without compromising the surface integrity of these ceramics.

Collectively, the studies of this thesis support the clinical feasibility of incorporating Er:YAG lasers into restorative workflows, not only for their efficiency in prosthesis retrieval but also for their potential role in preserving and reusing high-value ceramic restorations.

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