



**TURUN  
YLIOPISTO**  
UNIVERSITY  
OF TURKU

# Laser-Assisted Endodontics

Impact of Laser Modalities on Root Canal  
Cleaning, Adhesion and Mechanical  
Properties of Intraradicular Dentin

Jaana Hannele Sippus





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*To my beloved Family  
for always encouraging me when I needed support, and for their unconditional love.*

UNIVERSITY OF TURKU

Faculty of Medicine

Institute of Dentistry

Department of Cariology and Restorative Dentistry

JAANA HANNELE SIPPUS: Laser-Assisted Endodontics: Impact of Laser Modalities on Root Canal Cleaning, Adhesion, and Mechanical Properties of Intraradicular Dentin

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## ABSTRACT

Laser-assisted endodontic techniques have emerged as adjuncts to conventional chemo mechanical protocols in Endodontics, aiming to improve root canal cleaning and disinfection.

This series of *in vitro* studies aimed to investigate the effects of laser-assisted endodontic protocols on root canal cleaning, intraradicular bonding and root dentin integrity.

The first study evaluated the efficacy of Er:YAG laser using photon-induced photoacoustic streaming (PIPS) and Preciso tips for smear layer removal in root canals. The second study examined whether erbium lasers with modified fiber tips could improve bonding of fiber posts to intraradicular dentin assessing the nano leakage, and pushout bond strength. The third study was assessed the impact of Er:YAG, Er,Cr:YSGG and 940 nm diode lasers on mechanical properties of radicular dentin.

Results demonstrated that laser-assisted photoacoustic streaming and Preciso techniques both improved cleaning in the coronal and middle regions of the root canal, while bond strengths were significantly higher at the apical area. Laser irradiation reduced adhesive failures, cement-dentin gap formation, and nano leakage in apical sections, enhancing uniform adhesive bonding interfaces. Although the laser protocols did not significantly affect flexural strength, the highest fatigue strength was observed in erbium treated groups, with endurance limits remaining comparable across protocols.

**KEYWORDS:**Lasers, Er:YAG, Er,Cr:YSGG, Bonding, Fatigue

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## TIIVISTELMÄ

Lasertekniikka on viime aikoina soluttautunut laajasti osaksi perinteistä hammashoitoa. Useat tuoreet tutkimukset ovatkin keskittyneet laserhoitojen mahdollisuuksiin juurihoidoissa varsinkin niiden hyvän desinfektio kyvyn takia.

Tämän tutkimussarjan tarkoituksena oli arvioida laserhoidon erityisiä vaikutuksia syväpuhdistuksessa sekä sidostamisessa. Kaikissa erbium-lasereilla tehdyissä juurihoitotutkimuksissa käytettiin fotoakustista tekniikkaa ilman yleisiä biokemiallisia huuhteluaineita.

Alkuasetelmana oli juurikanavien syväpuhdistus uusia 360°:n säteilyn mahdollistavia lasikuitu kärkiä hyödyntäen. Seuraava tutkimus keskittyi puhdistavaan vaikutukseen syvemmissä kerroksissa, sekä saumavuodon ja sidoslajuuden analysointiin. Kolmas tutkimus keskittyi rasiustestiin, juurihoitojen usein heikentäessä hampaiden rakennetta, mikrohalkeamia aiheuttaen. Tässä vaiheessa otettiin mukaan myös diodi laser. Kaikki testit tehtiin yleisimpiä juurihoitokärkiä käyttäen erbium lasereilla ja 940 nm diodilla.

Fotoakustisella puhdistuksella saadut tulokset osoittivat tilastollisesti merkittäviä eroja juurikanavan ylä- ja keskiosissa, kun taas erbium laserilla aikaansaatu kavitaatio ei tehostanut vaikutusta paljoakaan apikaalisesti. Adheesiota arvioitaessa syväpuhdistuksen jälkeen havaittavat sidoslajuudet olivat merkittävästi korkeampia juuren kärjen läheisyydessä. Lasersäteily voi vähentää sidosongelmia sementin ja dentiinin rajapinnoilla, sekä saumavuotoa kärkialueella. Kaikki laserprotokollat, joissa käytetään uuden mallisia juurihoitokärkiä, voivat merkittävästi parantaa dentiinin, hartsin ja lasikuitunastojen välisiä sidosrajapintoja. Laserprotokollat eivät saavuttaneet merkittävää vaikutusta taivutuslujuuteen. Kuitenkin parhaimmat voimat esiintyivät erbium-käsitellyissä ryhmissä. Myös huippukestävyysrajat nousivat samoin, ollen selkeästi kontrolliryhmiä parempia.

AVAINSANAT: Laser, Sidostus, Rasiituslujuus

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# Abbreviations

AFM	Atomic force microscopy
ANOVA	Analysis of variance
C-factor	Ratio of the bonded to the unbonded surface area
CHX	Chlorhexidine digluconate
CLE	Conventional laser endodontics
CNI	Conventional needle irrigation
CW	Continuous wave
DT	Dentin tubules
EDDY	Sonic activation system
EDTA	Ethylenediaminetetraacetic acid
Er:YAG	Erbium-doped, Yttrium, Aluminium, garnet laser
Er,Cr:YSGG	Erbium, chromium-doped, yttrium, scandium, gallium, garnet laser
FDA	US Food and Drug Administration
FS	Flexural strength
FT	Fibre tip
GI	Glass ionomer
GP	Gutta-percha
h	Unit of time, hour
HA	Hydroxyapatite
Hz	Hertz, cycles per second
HMDS	Hexamethyldisilazane
ICTP	Pyridinoline cross-linked telopeptide
LAI	Laser activated irrigation
MDA	Manual dynamic activation
min	Unit of time, minute
mK	Unit of thermal conductivity, meter Kelvin
mm	Millimeter
MMP	Metalloproteinase
MPa	Megapascal
MSP	Micro short pulse
MTAD	Mixture of tetracycline, acid and detergent

NaCl	Sodium chloride
NaN <sub>3</sub>	Sodium azide
NIR	Near-Infrared-Laser
nm	Nanometer
Nd:YAG	Neodymium-doped, Yttrium, Aluminium; garnet laser
NI	Needle irrigation
PBS	Phosphate-buffered saline
PBMT	Photobiomodulation therapy
PIPS	Photon Induced Photoacoustic Streaming
RC	Root canal
RCT	Root canal treatment
RFT	Radial firing tip
s	Unit of time, second
SP	Short pulse
SAI	Sonically activated irrigation
SFRC	Short Fibre-Reinforced Composite
SNI	Syringe and needle irrigation
SiC	Silicon carbide
SEM	Scanning electron microscope
SL	Smear layer
SWEEPS	Shock Wave Enhanced Emission Photoacoustic Streaming
TRT	Thermal relaxation time
UAI	Ultrasonic Activated Irrigation
w/w	Weight in weight
XeCl	Xenon monochloride
XP	XP-endo finisher
μs	Unit of time, microsecond
μm	Micrometer

# 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 **Sippus JH**, Gutknecht N. Deep disinfection and tubular smear layer removal with Er:YAG using photon-induced photoacoustic streaming (PIPS) versus laser-activated irrigation (LAI) techniques. *Lasers in Dental Sciences*. 2019;3:37–42.  
doi:10.1007/s41547-018-0050-3
- II **Sippus JH**, Stape THS, Tezvergil-Mutluay A. Evaluation of Er:YAG and Er,Cr:YSGG lasers on intraradicular bonding using modified glass fiber tips. *Dental Materials Journal*. 2023;42(6):766–773.  
doi:10.4012/dmj.2023-025
- III **Sippus JH**, Capitanio M, Mutluay MM, Franzen R, Tezvergil-Mutluay A. Evaluation of Er:YAG, Er,Cr:YSGG and diode laser irradiation on radicular dentin fatigue strength using modified endodontic laser tips. *Biomaterial Investigations in Dentistry*. 2025;12:202–209.  
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# 1 Introduction

Successful endodontic therapy relies on the throughout removal of microorganisms from the root canal complex (Siqueira et al., 2009), and the long-term preservation of the structural and mechanical integrity of radicular dentin. Despite continuous advances in endodontic instruments, materials, and techniques, complete decontamination of the multifaceted root canal structure remains a substantial clinical task (Torabinejad et al., 2002). Anatomical variations like isthmuses, lateral canals, and dentinal tubules limit the effectiveness of conventional mechanical instrumentation and irrigant delivery, often allowing residual bacteria and smear layer to persist (Garcez et al., 2006). These restrictions have prompted the exploration of adjunctive methods focusing at improving root canal cleaning while preserving dentin structure (Gu et al., 2009).

Root canal irrigation has a crucial function in Endodontic therapy by facilitating tissue dissolution, microbial reduction, and smear layer removal (Peters et al., 2011). Conventional syringe irrigation, although widely used, is limited by inadequate irrigant penetration and stagnation, particularly in the apical third of the canal. Even applying advanced irrigants like sodium hypochlorite and chelating agents, the smear layer may not be completely removed, and bacteria may survive within dentinal tubules (De Moor et al., 2010; Tong et al., 2023). These limitations have prompted the development of irrigation activation techniques aimed at improving irrigant dynamics and enhancing cleaning efficacy.

Among these innovations, laser-assisted Endodontics has gained increasing attention. Dental lasers offer unique advantages based on their wavelength-dependent interactions with dental tissues and fluids (Liu et al., 2022; Meire & De Moor 2024). Particularly Erbium lasers, namely *Erbium-doped Yttrium Aluminium Garnet* [Er:YAG (2.940 nm)] and *Erbium Chromium-doped Yttrium Scandium Gallium Garnet* [Er,Cr:YSGG (2.780 nm)] exhibit high absorption in water and hydroxyapatite (HA), making them especially appropriate for hard tissue applications and endodontic procedures (Fried et al., 2002, Kömerik et al., 2003; Vogel & Venugopalan, 2003; Zhu et al., 2013). Their ability to induce photoacoustic and photomechanical effects has opened new possibilities for improving root canal disinfection without excessive thermal damage (Huang et al., 2023).

Laser-Activated Irrigation (LAI) utilizes pulsed laser energy delivered into irrigants within the root canal to generate cavitation bubbles and shockwaves that enhance fluid movement and debris, and biofilm detachment until thorough removal (George et al., 2008; De Moor et al., 2010; Meire et al., 2014, Swimberghe et al., 2022). Later, a more refined approach, Photon-Induced Photoacoustic Streaming (PIPS), employs ultra-short, low-energy laser pulses positioned coronally to produce powerful photoacoustic effects throughout the canal system. While applied only in pulp chamber instead of inside the root canal, PIPS has demonstrated promising results in enhancing smear layer removal and microbial reduction while minimizing direct contact with radicular dentin (DiVito et al., 2011; Olivi et al., 2014). However, variations in laser parameters, tip design, and activation techniques have a meaningful effect on outcome of LAI and necessitate further comparative evaluation of these modalities to establish their relative efficacy and safety.

Beyond disinfection, the condition of radicular dentin following irrigation and laser application is of paramount importance. Dentin is a biologically and mechanically complex tissue (Tjäderhane et al., 2009). The structural integrity of dentin is essential for the enduring success after endodontic treatment. Alterations in dentin microstructure, dentin moisture, collagen integrity, and mineral composition can influence its mechanical behaviour and bonding characteristics (Huang et al., 1992). Excessive thermal or chemical insult may weaken dentin, increase susceptibility to microcrack formation, and compromise fatigue resistance—factors closely associated with vertical root fracture and post-treatment failure.

Intraradicular bonding represents another critical aspect of endodontic rehabilitation, particularly in teeth requiring post placement. The bonding of glass fiber posts to radicular dentin is influenced by the occurrence of the smear layer, dentinal tubule openness, surface energy, and the condition of the collagen matrix. Conventional irrigation protocols may adversely affect bonding by altering dentin surface chemistry or leaving residual debris. Erbium lasers, through their ability to modify dentin morphology and remove the smear layer, have been proposed as potential tools to enhance intraradicular bonding. Previous research has demonstrated that erbium lasers affect not only dental hard tissues but also the surface characteristics of composite resins (Özer et al., 2013). Additionally, the development of modified glass fibre laser tips offers new possibilities for delivering laser energy more effectively within the root canal, potentially improving bonding outcomes while maintaining dentin integrity.

Another emerging concern in Endodontics is the impact of therapeutic procedures on the fatigue strength of radicular dentin. Unlike static fracture resistance, fatigue strength reflects the ability of dentin to withstand repeated functional stresses over time. Chemical irrigants, mechanical instrumentation, and thermal procedures can all influence dentin's fatigue behaviour. While erbium lasers

are generally considered safer than other laser systems due to their high water-absorption and limited depth of penetration, their long-term effects on radicular dentin fatigue strength, especially when used with modified endodontic tips, remain insufficiently explored. Such as tip positioning plays an important role, as placement within the root canal increases the likelihood of contact between the tip and the dentinal wall.

The growing body of literature on laser-assisted Endodontics highlights the need for an integrated evaluation of these technologies, considering not only their antimicrobial and cleaning efficacy but also their effects on dentin bonding and mechanical durability. Many previous studies have examined these outcomes in isolation, making it difficult to draw comprehensive clinical conclusions. A systematic assessment that links irrigation efficiency, adhesive performance, and dentin fatigue behaviour is essential for determining the true clinical feasibility of erbium laser applications in Endodontics.

Hence, the goal of this thesis is to examine the outcomes of Er:YAG and Er,Cr:YSGG laser systems on key aspects of endodontic treatment using advanced and modified laser delivery techniques.

## 2 Review of the Literature

### 2.1 Tooth Structure and Mechanical Properties

#### 2.1.1 Enamel

Dental enamel, covering the visible tooth crown can be considered as a natural ceramic. Enamel is the utmost mineralized tissue in the mammalian body, with a composition of around 85% vol inorganic material, mainly formed of carbonated hydroxyapatite crystals  $[\text{Ca}_{10}(\text{PO}_4)_6(\text{OH})_2]$ . The rest comprises water, 12% vol, and proteins, 3% vol (Sakae & Okuda, 1985).

The organic matrix plays an essential adhesive role, binding hydroxyapatite crystals, and organizing them into complex structural units, namely enamel rods, and prisms, This organization enhances both the mechanical resilience and optical properties of the enamel (Bachmann et al., 2004). Although present only in trace amounts, these organic components allow for subtle, coordinated movement between adjacent enamel rods, which helps dissipate stress and limits the propagation of cracks within the structure (He & Swain, 2007).

#### 2.1.2 Dentin

Dentin, the tissue underneath the enamel shell, comprises the bulk of tooth structure. It is the second most highly mineralized tissue in human body and plays a critical biomechanical role by preventing crack propagation from the enamel surface into deeper tooth tissues (Imbeni et al., 2005). Structurally, dentin can be regarded as a fibre-reinforced, tubular composite material (Kruzic et al., 2005; Tjäderhane et al., 2009). Dentin consists of tubules with diameters varying from 0.8  $\mu\text{m}$  near the dentin-enamel junction up to 3  $\mu\text{m}$  near the pulp. It consists of hyper mineralized peritubular dentin and, to a lesser extent, mineralized intertubular dentin. Dentinal tubules are filled with liquid, hydrating the dentinal matrix and acting as a conductor of peripheral stimuli to the pulpal nerves (Ajcharanukul et al., 2011).

The dentin matrix is a humid bio composite of organic and inorganic components. Its inorganic phase consists of carbonated making up around 47% by volume (or 70% wt). However, the hydroxyapatite crystals in dentin are tinier and

comprise a higher carbonate content than those in enamel, executing dentin more susceptible to acid dissolution. Compared to enamel, dentinal structure is more heterogeneous, containing 20% ratio organic matrix. The mineralized dentin has a considerably greater volume of water (10% vol, or 22% wt of dentin organic matrix) compared to enamel (12% vol, or 3% wt) (Bachmann et al., 2004).

Collagen represents around 90% vol of organic components of dentin, predominantly type I collagen (Tjäderhane et al., 2009) with smaller quantities of types III and V collagen also present (Goldberg et al., 2011). Dentin collagen is highly crosslinked, distinguishing it from soft-tissue collagen in terms of mechanical properties and stability (Schlueter, 1963). Ramifications connecting nearby tubules with multiple anastomoses create a massive branching structure, mainly in cases when the thickness of the central tubule is slight (Mjör & Nordahl, 1996). Water is principally found inside the dentinal tubules (Tjäderhane et al., 2009). Moisture levels between superficial and deep dentin may vary by as much as twentyfold (Pashley, 1996), contributing to the high permeability and a pressurized outward flow of dentinal liquids, otherwise referred to as pulpal pressure. In addition, there is potential for an inward flow of microscopic components, the extent of which is dependent on the specific pathological conditions present.

Peritubular dentin located with the inner walls of the tubules, is highly mineralized and lacks collagen fibrils, comprising a mineral-rich organic scaffold. Intertubular dentin, by contrast, contains a collagen matrix scattered between the dentin tubules (Bertassoni et al., 2012). The odontoblast processes extending into the tubules play a key role in regulating the dynamical reaction of dentin to external stimuli and maintaining dentin vitality (Bertassoni et al., 2012; Giudice et al., 2015).

### 2.1.3 Characteristics of Root Dentin

While coronal dentin is surrounded by enamel, root dentin is covered by cementum, both of which protect the underlying dental pulp. Root dentin is usually less dense and mineralized than coronal dentin, with 65–70% hydroxyapatite. The dentin tubules extend from the pulp to cementum (Mjör et al., 2001). While root dentin is dynamic in terms of elasticity, it is vulnerable to hypersensitivity and decay when exposed to oral environment (Giudice et al., 2015). Compared to crown dentin, root dentin has a lower density and smaller diameter of dentinal tubules, shows more branching (ramifications), and has reduced permeability (Mjör et al., 2001). In the apical section, dentin is more irregular with sclerotic dentinal tubules obliterated by minerals (Paque et al., 2006). It is important to recognise the correlation between the microstructure and the properties of dentin.

### 2.1.4 Intraradicular Bonding

Today's trend has shifted from routine use of posts to placing them only when necessary. Short Fiber-Reinforced Composites (SFRC) in dentistry are advanced restorative materials designed to overcome the limitations of conventional composites, particularly in large, load-bearing cavities. However, restoring teeth after of endodontic treatment still involves the use of intraradicular posts to retain the coronal restoration, especially in cases with extensive loss of tooth structure. Glass-fibre posts have gained widespread acceptance due to their favourable elastic modulus, which is like dentin, promoting more uniform stress distribution and diminishing the probability of disastrous root fractures when compared to metallic posts (Mannocci et al., 2005; Ferrari et al., 2012). However, the long-term clinical success of fibre-reinforced post systems largely relies on the quality and durability of adhesive bonding to radicular dentin.

Achieving durable intraradicular bonding is more challenging compared to bonding to coronal dentin due structural differences such as lower density of dentinal tubules, reduced permeability, variations in mineral content and the presence of smear layer remnants (Ferrari et al., 2012). Additionally, intraradicular bonding is performed under unfavourable conditions, including limited visibility, restricted access, difficulty in moisture control and a high configuration factor (C-factor), which significantly increases polymerization shrinkage stresses within the adhesive interface (Tay et al., 2005).

Surface modification of radicular dentin plays a critical role in bonding performance. The presence of the smear layer created throughout root canal instrumentation and post-space preparation further compromises bonding effectiveness. This layer occludes dentinal tubules and may interfere with adhesive infiltration, resulting in weak hybrid layer formation and reduced bond strength (Serafino et al., 2004). Moreover, remnants of endodontic sealer and irrigants can contaminate the dentin surface, negatively affecting resin polymerization (Kazeminejad et al., 2021) and adhesion (Ekambaram et al., 2015; García-Varela et al., 2024; Tonga et al., 2025).

### 2.1.5 Smear Layer in Endodontics

Instrumentation of the root canal system consequences in the creation of an unstructured coating, recognised as smear layer, comprised of organic and inorganic debris, bacteria, necrotic tissue remnants, and odontoblastic processes (McComb & Smith, 1975).

Brännström and Johnson (1974) observed a thin film of debris on dentin surfaces following cavity preparations, measuring approximately 2–5 µm in thickness and extending into dentinal tubules. However, the smear layer formed throughout root

canal treatment diverges from the layer seen on coronal dentin because of the confined tubular anatomy and presence of pulpal tissue (Brännström & Johnson, 1974). McComb and Smith (1975) were the first to characterize the smear layer on root canal walls utilizing scanning electron microscopy (SEM), identifying a uniform 2–5  $\mu\text{m}$  thick, microcrystalline coating composed of organic and inorganic components. Goldman colleagues (1982) later on demonstrated that the smear layer in endodontically treated canals can be approximately 1  $\mu\text{m}$  thick and predominantly inorganic. Regardless of slight variations reported across studies, the smear layer is consistently recognized as a barrier that may hinder infiltration of irrigants, pharmaceuticals and sealants into dentinal tubules (Breschi et al, 2009, Violich and Chandler, 2010). **Figure 1** illustrates an SEM image exemplifying a dense smear layer completely covering intraradicular surface covering the tubules.



**Figure 1.** A representative SEM image showing a very even smear layer covering the coronal part of a canal wall. The whole dentin surface is concealed, and dentinal tubules are not exposed. (picture Jaana Sippus)

Mader et al. (1984) provided further SEM evidence by revealing that the smear layer comprises of a superficial layer (1–2  $\mu\text{m}$  thick) and a profounder component that could prolong into the tubules up to 40  $\mu\text{m}$ . These deeper “finger-like” projections can be especially resistant to removal.

The clinical relevance of smear layer removal remains debated; however, numerous studies suggest that its elimination improves sealer adaptation, enhances intraradicular bonding, and reduces bacterial leakage (Torabinejad et al., 2002).

From an adhesion perspective, removing the smear layer increases dentin permeability and promotes deeper penetration of adhesive monomers into the demineralized collagen network, thereby improving the formation and quality of the hybrid layer (Breschi et al., 2009; Violich & Chandler, 2009; Özcan et al., 2020).

### 2.1.6 Irrigation Solutions Used in Endodontics

Conventional irrigation protocols typically employ sodium hypochlorite for organic tissue dissolution and antimicrobial action, subsequently using chelating agents like ethylenediaminetetraacetic acid (EDTA) to eradicate the inorganic component of the smear layer (Haapasalo et al., 2014; Ordinola-Zapata et al., 2014; Martins et al., 2018). Despite their widespread use, these solutions exhibit limited penetration into the apical third and complex anatomical regions when delivered via syringe irrigation alone (Boutsioukis et al., 2010).

Traditional syringe irrigation is constrained by low flow rates, limited apical penetration, and vapor lock formation, particularly in closed canal systems (Tay et al., 2010). To overcome these limitations, various irrigation activation techniques have been elaborated, including manual dynamic agitation, sonic activation, and passive ultrasonic irrigation (PUI).

Passive ultrasonic irrigation has demonstrated enhanced smear layer removal and microbial diminution related to syringe irrigation due to acoustic streaming and cavitation effects (van der Sluis et al., 2007). Nevertheless, PUI requires close proximity to canal walls, and its efficacy may be reduced in curved or narrow canals. Moreover, ultrasonic tips may inadvertently contact dentin, increasing the risk of canal transportation or microcrack formation (Meire et al., 2010; De Moor et al., 2010; Martins et al., 2012). A later study could confirm that wall contact of the file during ultrasonic activation of the irrigant occurred in all cases. Therefore, it was concluded that the term 'Passive Ultrasonic Irrigation' should be revised to 'Ultrasonically Activated Irrigation' (UAI) (Boutsioukis et al., 2013).

These limitations have encouraged further exploration of laser-based irrigation activation as a non-contact alternative capable of enhancing irrigant dynamics throughout the comprehensive root canal structure (Meire et al., 2023).

### 2.1.7 Mechanical Properties and Fatigue Resistance of Radicular Dentin

The long-term success of endodontically treated teeth not only depends on effective cleaning and disinfection and adequate restoration but also on the preservation of the mechanical integrity of radicular dentin. Mechanical instrumentation may introduce microcracks due to excessive forces or inappropriate file design, particularly in

curved canals (Shemesh et al., 2010). These microcracks can act as stress concentrators, facilitating crack propagation under functional stresses during mastication, parafunctional habits, and restorative loading. These stresses may lead to the propagation of microcracks, ultimately resulting in fatigue failure or vertical root fracture, which represent one of the most unfavourable outcomes in Endodontics (Arola & Reprogl, 2005).

The structural variations in radicular dentin such as tubule density, diameter, orientation and mineralization contribute to differences in elasticity, hardness, fracture resistance of the root. The elastic modulus of radicular dentin allows it to deform under load, dissipating stresses and protecting the root against sudden fractures. However, the changes in mineral-organic balance of dentin can compromise this protective mechanism. Procedures that excessively demineralize dentin matrix may reduce dentin toughness and increase susceptibility to crack initiation (Lee et al., 2014).

Traditionally, fracture resistance has been evaluated using static loading tests, however, such tests do not accurately reflect clinical conditions. In oral environment, teeth are exposed to cyclic subcritical loads rather than single overload events. Fatigue failure occurs when repeated stresses induce microscopic damage that accumulates over time, eventually leading to catastrophic fracture at stress levels well below the static fracture threshold (Arola et al., 2010).

Fatigue strength is referred to the highest stress level a material can endure for a given number of loading cycles without experiencing failure. Studies have demonstrated that dentin is particularly susceptible to fatigue fractures, especially when its microstructure is altered by chemical or mechanical treatments (Bajaj et al., 2006). Therefore, fatigue testing provides a more clinically relevant assessment of dentin durability than static fracture testing alone.

Endodontic treatment procedures can significantly affect the mechanical integrity of radicular dentin. Mechanical instrumentation may introduce microcracks due to excessive forces or inappropriate file design, particularly in curved canals (Shemesh et al., 2009). These microcracks can act as stress concentrators, facilitating crack propagation under cyclic loading.

Chemical irrigation protocols also play a critical role in modifying dentin properties. Sodium hypochlorite, widely used for its antimicrobial and tissue-dissolving properties, has been shown to degrade the organic collagen matrix, leading to reduced flexural strength, elastic modulus, and fracture resistance of dentin (Zhang et al., 2010). Prolonged exposure or high concentrations exacerbate these effects.

Chelating agents such as EDTA remove the inorganic component of dentin, reducing microhardness and altering mineral density (Calt & Serper, 2002). When used in combination, sodium hypochlorite and EDTA may synergistically weaken dentin by disrupting both organic and inorganic components. These alterations are

particularly concerning in radicular dentin, where structural thickness is limited and functional stresses are concentrated. The presence of intraradicular posts can further influence stress distribution, potentially increasing stress concentration in the apical and middle thirds of the root if bonding is inadequate or if dentin properties are compromised (Mannocci et al., 2005).

Thermal procedures may adversely affect dentin mechanical properties by causing dehydration, collagen denaturation, or microstructural changes. Lasers, depending on wavelength and energy parameters, can generate heat within dental tissues (Dela Bosa et al., 2004). Excessive temperature rise may lead to irreversible damage to the collagen matrix and reduced dentin toughness.

Erbium lasers are considered comparatively safe for endodontic applications because of their high absorption co-efficient in water and shallow penetration depth. This interaction limits heat transmission into deeper dentin layers and surrounding periodontal tissues (Coluzzi, 2004). Several studies have reported minimal changes in dentin microhardness and flexural strength following erbium laser irradiation when appropriate parameters are used (Esteves-Oliveira et al., 2009)].

Nevertheless, the impact of erbium laser irradiation on dentin fatigue behaviour remains insufficiently investigated. While surface modification may enhance bonding or cleaning efficacy, alterations at the microstructural level could influence crack initiation and propagation under cyclic loading. The role of laser tip design, energy distribution, and irradiation time is therefore critical in determining the mechanical outcomes.

## 2.1.8 Endodontic Challenges

Endodontic treatments focus on eradicating infection of the root canal structure and preventing reinfection. However, the anatomical complexity of root canals poses significant challenges to achieving complete disinfection. The occurrence of lateral canals, apical deltas, isthmuses, and c-shaped canals jeopardize successful cleaning and shaping, limiting the effectiveness of mechanical instrumentation alone, as files are unable to contact all canal walls uniformly (Peters, 2004). Consequently, residual bacteria and organic debris may persist even after meticulous chemo mechanical preparation.

Microorganisms located within dentinal tubules are of particular concern, as they may penetrate several hundred micrometers into the dentin and remain protected from irrigants and intracanal medicaments (Haapasalo & Ørstavik, 1987; Huang et al., 2024; Mehta et al., 2025). These residual microorganisms have been implicated in persistent periapical inflammation and endodontic treatment failure. Therefore, effective irrigation strategies that enhance disinfecting efficacy beyond mechanical instrumentation are essential (Duncan et al., 2023).

## 2.2 Dental Lasers

### 2.2.1 Characteristics Of Dental Lasers

Laser light is *monochromatic* (single-color), *coherent*, and highly *collimated*, and is generated by stimulated emission of radiation, which stands for *Light Amplification by Stimulated Emission of Radiation (LASER)*. Unlike conventional light sources, laser beams maintain their directionality over long distances with minimal divergence, which supports their use in precise, high-energy applications across medicine, industry, and technology. Dental lasers operating in the invisible infrared spectrum require an auxiliary pilot beam to assist with visualization during clinical procedures, as is the case with diode and erbium lasers. This guiding beam helps clinicians identify the working area when the operative wavelength itself cannot be seen (Coluzzi, 2000).

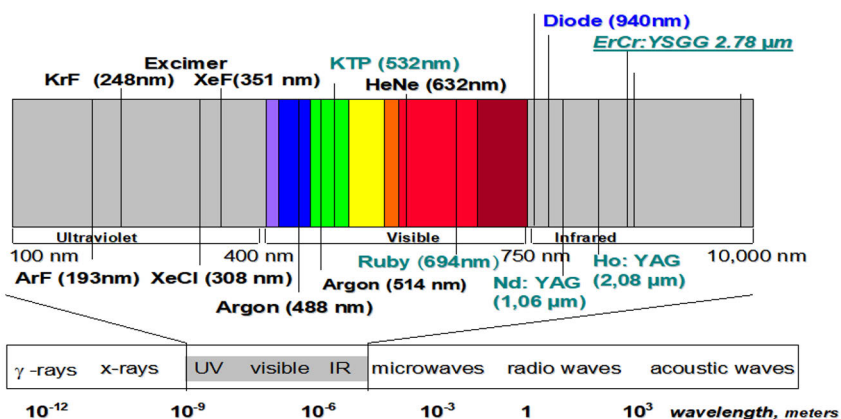
Laser systems are commonly categorized according to their gain medium. This medium may be solid-state, gas, semiconductor, or liquid. The gain medium determines both wavelength and power output. Dental laser systems operate in either continuous or pulsed emission modes (Coluzzi & Convissar, 2011). In continuous mode, energy is delivered at a constant rate, whereas in pulsed mode, intermittent on-off emission allows greater control over thermal effects (Coluzzi & Convissar, 2011).

Single- and dual-pulse dental laser systems provide greater precision than continuous-wave lasers. Single-pulse modes, such as Super Short Pulse (SSP), are effective for conventional ablation procedures. In contrast, dual-pulse technologies, including *Shock Wave Enhanced Emission Photoacoustic Streaming (SWEEPS®)*, generate enhanced photoacoustic effects that improve decontamination efficiency. Single-pulse lasers deliver discrete bursts of high-intensity energy suitable for hard-tissue ablation, soft-tissue incision, and coagulation, while allowing thermal relaxation between pulses and thereby reducing the risk of heat-related tissue damage. Compared with continuous-wave emission, short-pulse Er:YAG laser modes (such as SSP or SP) enable precise “cold” ablation by rapidly vaporizing water with minimal thermal impact on surrounding tissues.

The development of laser pulse technologies has advanced from Short Pulse (SP) to Variable Square Pulse (VSP) and, more recently, to Ultrashort Pulse (USP) systems. This represents a shift from thermally intensive processing to high-precision “cold” material interaction. The progression emphasizes increasing peak power while limiting heat transfer. This enables the formation of finer microstructures. USP lasers typically operate within the picosecond ( $10^{-12}$  s) and femtosecond ( $10^{-15}$  s) pulse-duration range. These allow nonlinear ablation mechanisms with minimal thermal diffusion to the surrounding material.

Key laser power and energy parameters include power, energy, energy density, repetition rate, and power density. Power (Watts – W) represents the rate at which laser energy is delivered, with higher power levels enabling faster tissue ablation but requiring careful control to avoid thermal injury. Energy (Joules – J) refers to the total amount of energy delivered and is calculated as the product of power and exposure time. Energy density (fluence, J/cm<sup>2</sup>) describes the amount of energy applied per unit area of the laser spot and plays a critical role in determining clinical outcomes. Repetition rate (Hertz – Hz) indicates the number of pulses emitted per second and influences the cumulative energy delivered during treatment. Power density (irradiance, W/cm<sup>2</sup>) is the rate of laser power per unit area and determines the laser's effectiveness for different clinical applications.

The earliest laser, the Ruby laser (693.4 nm), for cutting dentinal hard tissue was reported in 1960. Various wavelengths, such as *neodymium-doped yttrium aluminium garnet*, Nd:YAG (1.064 nm), *carbon dioxide*, CO<sub>2</sub> (10.600 nm), and *holmium-doped yttrium aluminium garnet*, Ho:YAG (2.120 nm), were subsequently investigated. However, although they produced substantial temperature increases, these wavelengths induced severe side effects in dental pulp, including carbonization and microcracks (De Moor et al., 2009). After the first lasers were discarded in hard-tissue procedures, new lasers were developed in the 1980s. An erbium laser in the infrared was explored with enhanced temperature control and a lower penetration depth. Improved knowledge led to new ablation methods, and lasers gained FDA approval in 1990 (Coluzzi, 2000; Gimbel, 2000). One of the biggest laser dentistry revolutions was the introduction of photo-acoustic shock waves (DiVito et al., 2011; Peters et al., 2011). Spectrum for different lasers are presented in **Figure 2**.



**Figure 2.** Spectrum for lasers in medicine and dentistry. (with permission from Biolase, USA)

## 2.2.2 Beam Diameter vs. Spot Size

The spot size denotes the minimum diameter of the laser beam diameter at the focal point, while the diameter of the laser beam is the width of the beam at other points (like when it exits the laser). The delivery techniques can be articulated arms with mirrors or hollow waveguides (Gimbel, 2000). There is an exact focal spot where the energy amount is the highest. The precise, focused spot is advantageous in surgical procedures like incision or excision. The focal spot, with the most significant energy amount, is at the tip or in the proximity of the fibre for fibre-optic contact delivery systems. Halving the spot size increases the energy or power density by 4. Moving the handpiece further from the target surface and zooming out from the focused spot, the laser irradiation becomes defocused, deviating. It delivers laser energy to the operational location to a lesser extent. For some specific procedures, like slight tissue ablation or haemostasis, this could be useful when the beam can cover a larger zone at a minor divergent space. When the distance increases, the efficiency of the beam drops because of the dissipating energy (Carroll & Humphreys, 2006).

## 2.2.3 Impact of Pulse Duration

High-intensity lasers are increasingly integrated into contemporary dental practice due to their versatility in treating both soft and hard tissues. The therapeutic outcome of laser-assisted procedures depends largely on adjustable parameters such as wavelength ( $\lambda$ ), pulse energy (W), pulse duration (s), and repetition rate (Hz). These parameters allow selective treatments of dental tissues and removal while minimizing patient discomfort and improving procedural efficiency (Bandéca et al., 2012; Komori, 1997). Among these variables, pulse duration plays a particularly important role in determining treatment precision, thermal interaction, and overall safety.

### 2.2.3.1 Different Pulse Durations

Pulse duration is one of the most critical determinants of laser–tissue interactions. Thermal relaxation time (TRT) represents the duration required for tissue to dissipate absorbed heat following laser exposure. Adjusting pulse length according to TRT allows for controlled thermal effects, optimizing tissue ablation while minimizing thermal damage to surrounding structures. The thermal relaxation time of enamel is approximately 100  $\mu$ s, which serves as an important reference when selecting appropriate pulse durations for clinical procedures (Ismail et al., 2025). Based on this parameter, commonly applied Er:YAG pulse-durations include:

- Super short pulse (SSP, 50  $\mu\text{s}$ ): optimized for precise hard-tissue ablation
- Micro short pulse (MSP, 100  $\mu\text{s}$ ): standard clinical applications
- Short pulse (SP, 180  $\mu\text{s}$ ): routine operative procedures
- Long pulse (LP, 350  $\mu\text{s}$ ) and very long pulse (VLP, 700–1000  $\mu\text{s}$ ) primarily used for soft-tissue procedures requiring coagulation

Er,Cr:YSGG lasers (2780 nm) operate similarly in pulsed mode, typically employing short-pulse (H mode) or microsecond-range pulses (e.g., 140–150  $\mu\text{s}$ ) to target water and hydroxyapatite.

Pulse duration is one of the most critical determinants of laser–tissue interaction and ablation efficiency. Advances in laser technology now allow the adjustment of pulse durations across a wide temporal spectrum, ranging from microseconds ( $10^{-6}$  s) to nanoseconds ( $10^{-9}$  s), picoseconds ( $10^{-12}$  s), and femtoseconds ( $10^{-15}$  s) (Shariati et al., 1993).

Fresh study has shown that similar to pulse energy, pulse duration has a significant influence on erbium laser–induced cavitation. However, the correlation is inverse: when pulse energy is held constant, shorter pulses produce larger vapor bubbles (Meire & De Moor 2024). Earlier studies have likewise shown that shorter pulses produce larger vapour bubbles (Gregorčič et al., 2012). Therefore, to achieve the highest cavitation efficiency, the shortest possible pulse duration appears to be the preferred option. However, this parameter varies between laser devices; currently available minimum pulse durations range from 25  $\mu\text{s}$  to 200  $\mu\text{s}$ .

### 2.2.3.2 Thermal Effects

Laser-tissue interactions are highly dependent on the thermal properties of the targeted tissues, particularly their water content and capacity to absorb heat. Understanding these thermal effects is essential for optimizing surgical outcomes and minimizing collateral tissue damage. Effective laser application in both soft and hard tissues hinge on precise control of operational parameters—including energy, pulse duration, duty cycle, and water/air combination. Mastery of these factors ensures selective tissue removal, enhanced surgical precision, and reduced postoperative complications.

Excessive thermal energy generated during laser irradiation may result in undesirable peripheral tissue damage. Potential adverse effects include:

- formation of cracks or fractures in hard tissues,
  - disruption of dentinal structure,
  - melting of enamel or dentin surfaces, and
  - delayed healing or bone necrosis
- (Shariati et al., 1993; Staninec et al., 2008; Franzen et al., 2016)

To minimize these risks, pulse durations shorter than the TRT of the target tissue should be selected. When pulse durations exceed this threshold, heat diffuses deeper into surrounding tissues, increasing the likelihood of thermomechanical trauma (Kimura et al., 1997). Consequently, shorter pulse durations are generally preferred because they promote precise ablation while preserving adjacent tissue integrity (Dela Bosa et al., 2004).

### 2.2.3.3 Ablation Threshold

Hibst and Keller were the first to exhibit that Er:YAG laser ablation of hard tissue could be performed without carbonization, melting, or pulpal damage when proper water cooling was used (Keller & Hibst, 1997).

The primary mechanism of erbium-laser induced dental ablation is water-mediated micro explosion, where rapid vaporization of water within the dentin matrix results in particle ejection. However, *sub-ablative* parameters are commonly used in endodontics. The aim in root canal treatments is to promote hydrodynamic cleaning rather than hard tissue removal (DiVito et al., 2012). Scanning electron microscopy (SEM) studies have identified *ablation thresholds* for both erbium lasers. The Er:YAG laser presents an ablation threshold of 3–3.5 J/cm<sup>2</sup>, while Er,Cr:YSGG laser around 2.7–3.7 J/cm<sup>2</sup> (Lin et al., 2010).

Experimental studies have demonstrated that shorter pulse durations reduce the energy threshold required for ablation. Apel et al. reported that reducing pulse duration when using Er:YAG lasers lowered the ablation threshold (Apel et al., 2002).

## 2.2.4 Laser Tissue Interactions With Target Substances

### 2.2.4.1 Main Types of Laser Interactions

The interaction between laser energy and biological tissues is determined primarily by the optical properties of the target tissue. Laser–tissue interactions occur through four principal mechanisms: *absorption*, in which energy is retained within the tissue; *transmission*, where radiation passes through the tissue without interaction; *reflection*, in which energy is redirected from the tissue surface; and *scattering*, characterized by the diffuse redistribution of photons within the irradiated tissue (Coluzzi & Convissar, 2011; Knappe et al., 2004).

In addition to these fundamental mechanisms, specific wavelengths may induce *photochemical interactions*, resulting in chemical alterations within the irradiated material. For example, argon laser irradiation has been used to initiate polymerization of composite resins (Walsh, 2003). Certain biological chromophores

may also emit fluorescence when exposed to selected wavelengths, a property utilized in diagnostic applications such as caries detection (Mercer, 1996; Walsh, 2003).

Another important mode of laser–tissue interaction is *low-level laser therapy (LLLT)*, which produces biostimulatory effects that enhance wound healing, promote collagen synthesis, reduce pain perception, and support anti-inflammatory responses. Furthermore, when laser energy is delivered in short pulses within an aqueous environment, it can generate pressure waves that produce *photoacoustic streaming*, a mechanism used as an adjunctive approach to laser-activated irrigation in hard-tissue procedures (DiVito et al., 2011; Gimbel, 2000).

Among the various interaction mechanisms, *photothermal interaction* is the most common and clinically relevant. In this process, absorbed laser energy is converted into heat, enabling applications such as surgical incision, hard- and soft-tissue ablation, and coagulation (Knappe et al., 2004; Walsh, 2003). The extent of these effects can be controlled by adjusting laser parameters including energy output, exposure time, and beam diameter.

Laser-assisted soft-tissue procedures offer several advantages compared with conventional techniques, particularly improved hemostasis and reduced postoperative discomfort. These clinical effects depend largely on the absorption characteristics of tissue chromophores, especially *water and haemoglobin*, which play a central role in determining laser–tissue interaction outcomes (Walsh, 2003).

#### 2.2.4.2 Soft Tissue Ablation and Protein Denaturation

Laser-induced heating affects soft tissues in a predictable manner. Protein denaturation begins at temperatures ranging from 60°C to 100°C, altering tissue structure without vaporization of underlying layers (Ishiwatari et al., 2013). When water within the tissue reaches 100°C, vaporization occurs, leading to ablation. This principle allows for precise excision or incision of soft tissues, as tissues with higher water content respond more effectively to laser irradiation. Controlled temperature application enables the selective removal of diseased tissue while preserving adjacent healthy structures (Knappe et al., 2004).

Moderate elevations in tissue temperature, typically between 70°C and 80°C, can induce tissue fusion at wound edges. This effect allows for wound closure without the need of sutures (Çilesiz et al., 1996). Conversely, excessive heating up to approximately 200°C results in carbonization, causing burned, scarred, and dehydrated tissue. Such outcomes are usually associated with improper adjustment of laser parameters.

### 2.2.4.3 Laser Operational Parameters

The *duty cycle*—defined as the ratio of laser “on” time to “off” time—plays a critical role in modulating tissue response. Slender or delicate tissues require shorter duty cycles, whereas denser or fibrous tissues may necessitate longer cycles or continuous-wave operation. While hard tissues require higher energy due to their mineral composition, dentin and soft tissues, with higher water content, are more responsive to lower energy levels.

### 2.2.4.4 Laser Types and Their Interaction with Dentine

Diode (and Nd:YAG) lasers primarily produce heat. There is no significant absorption in dentine, meaning their energy does not interact directly with the mineralized structure in a meaningful way. Erbium lasers (Er:YAG, Er,Cr:YSGG): Originally used in dried canals in a sub ablative mode, meaning their energy was below the threshold to remove tissue but could still induce subtle effects.

The practice of using laser fibers immersed in irrigation solutions did not become common until after 2007. Prior to this, lasers were primarily applied in dry canals. This distinction is important: only when fibers are in fluid can phenomena like cavitation and photoacoustic streaming occur. Diode and Nd:YAG lasers, when used in solution, do not generate cavitation, which limits their ability to enhance irrigation.

Before the widespread use of EDTA as a final rinse, many canals retained a glazed smear layer after instrumentation. When EDTA is used as a final rinse, dentinal tubules are open, and heat from lasers can penetrate deeper into the dentine, potentially increasing the impact of thermal effects. Therefore, the presence of a smear layer originally limited the effect of Nd:YAG and diode lasers on dentine.

Endodontics is “special” because the interaction of lasers with dentine is mediated by canal contents and tissue conditions. Heat-based lasers like diodes and Nd:YAG are limited in dried canals without EDTA; their effects are largely superficial or smear-layer dependent. The introduction of irrigation solutions and EDTA changes the thermal dynamics, making deeper energy penetration possible, but cavitation remains primarily a property of Erbium lasers.

### 2.2.4.5 Absorption of Laser Energy

Understanding laser-tissue interaction mechanisms is essential for selecting appropriate laser system and ensuring safe, effective treatment outcomes. Each laser wavelength exhibits a characteristic absorption profile that determines its interaction with specific tissue components, known as *chromophores*. Haemoglobin, oxyhaemoglobin, pigmented tissues, and dark materials have a strong absorption coefficient in specific wavelengths like diode lasers from 810 nm to 1.064 nm, and

Nd:YAG 1.064 nm, whereas water, the primary element in all biological tissues, exhibits a high absorption coefficient in both erbium wavelengths (Vogel et al., 2003). Lower wavelengths, diode, and Nd:YAG lasers are poorly absorbed by water and therefore transmitted more deeply through hydrated tissues (Yamakawa et al., 2018). Since dental tissues contain a complex mixture of organic and inorganic compounds, careful wavelength selection is crucial. Soft tissue treatments are more accessible since almost all available wavelengths can be used because one or more soft tissue components will absorb laser wavelengths (Coluzzi & Convissar, 2011). Hard tissue ablation, however, requires wavelengths with strong affinity for water and hydroxyapatite, erbium lasers, and the 10.600 nm CO<sub>2</sub> lasers are particularly effective, when used with short pulse durations limiting thermal diffusion (Sheth et al., 2004). Excessive penetration of laser energy might increase the risk of thermal injury, including tissue necrosis or osteonecrosis, if inappropriate parameters are applied (Ansari et al., 2013). Penetration depth, defined as the tissue thickness within 98% of the laser energy is absorbed, is a key determinant of thermal effects and overall tissue response for predicting the extend of thermal diffusion and tissue impact (Feynman, 2005).

## 2.3 Typical Wavelengths in Endodontics

Laser-assisted endodontic procedures typically employ the following systems: Er:YAG; Er,Cr:YSGG; Nd:YAG; Nd:YAP (neodymium: yttrium–aluminium–perovskite); CO<sub>2</sub> (carbon dioxide); and diode lasers (Kimura et al., 2000). The interaction of these wavelengths with dental tissues and their clinical applications in Endodontics are summarized in **Table 1**.

**Table 1.** Lasers used in endodontics.

Laser system	Wavelength	Laser-tissue interactions	Application	References
Diode	810–980 nm	*Absorbed in melanin, haemoglobin *Antimicrobial effect	*Bacteria eradication in root canals	(Kaplan et al., 2021; Matthew et al., 2022; Saydjari et al., 2016)
Nd:YAG	1.064 nm	*Scattering of energy and deep penetration in surrounding tissues	*Root canal irrigation	(Esteves-Oliveira et al., 2010; Hardee et al., 1994; Korkut et al., 2016; Q qiang Wang et al., 2007)
Nd:YAP	1.340 nm	*Absorbed in melanin, in melanin, haemoglobin, and water	*Smear layer removal from canal walls	(Armengol et al., 2000; Namour et al., 2016; Wang et al., 2005)
Er,Cr:YSGG	2.780 nm	*Absorbed in hydroxyapatite and water *High cutting effect using water spray, minimum heat	*Laser activated irrigation (LAI)	(Fattah et al., 2013)
Er:YAG	2.940 nm	*Highest absorption in water *Water mediated ablation, small temperature rise *Hard tissue ablation	*Laser activated irrigation (LAI), (as Er,Cr:YSGG) *Pulpotomy	(Vogel & Venugopalan, 2003; Hubbezoglu et al., 2013; Zan et al., 2016; Yamakawa et al., 2018; Bader et Krejci, 2006; Kokuzawa et al., 2012; Jwang et al., 2022)
CO <sub>2</sub>	10.600 nm	*Great absorption in enamel and dentin *Excellent hemostasis	*Multiple applications in medicine, and in direct pulp capping in dentistry	(Anice & Matsumoto, 1995; Luk et al., 2020; Melcer et al., 1985; Moritz et al., 1998)

## 2.3.1 Lasers in Near-Infrared Spectrum

### 2.3.1.1 Diode Lasers

The diode lasers are among the most used wavelengths in Dentistry, operating in near-infrared (NIR) spectrum between 810–980 nm (Saydjari et al., 2016). The clinical advantage of diode lasers is their higher absorption coefficient to water within dental hard tissues compared to Nd:YAG lasers, while still allowing deeper penetration into water-containing tissues. The penetration ranging from 1–3 mm, is dependent on the wavelength and targeted tissue, enables diode lasers to exert a strong antibacterial effect particularly in intertubular dentin (Mathew et al., 2022).

Among diode wavelengths, 980 nm exhibits a significant absorption peak in water, compared to wavelengths between 810 to 940 nm. Diodes present a wide group with low-power and high-power lasers, ranging nowadays up to 1.064 nm. Although diodes are absorbed less strongly by water compared to erbium lasers, their deeper penetration enhances effectiveness against pigmented microorganisms, making them suitable for both disinfection (de Souza et al., 2008; Fahim et al., 2024) and biomodulation (Fornaini et al., 2021; Kaplan et al., 2021; Duarte et al., 2026).

In addition to microbial decontamination, diode lasers have been utilized for photo-activated disinfection, biostimulation, and pain therapy contributing to the reduction of intra-operative and postoperative discomfort. When operated in rotational sweeping motion from the apical toward the coronal direction, diode lasers are considered safe and effective, if cooling intervals are respected to prevent excessive heat accumulation (Kaplan et al., 2021, Duarte et al., 2026).

## 2.3.2 Lasers in the Mid-Infrared Spectrum

### 2.3.2.1 Erbium Lasers

Erbium-family lasers are widely used in modern dentistry due to their strong interaction with water and hydroxyapatite, resulting in instantaneous vaporization and micro-explosions within hydrated dental structures (Vogel & Venugopalan, 2003). This makes them particularly suitable for hard-tissue procedures. The two most commonly applied systems are the erbium-doped yttrium aluminum garnet (Er:YAG) laser and the erbium, chromium-doped yttrium scandium gallium garnet (Er,Cr:YSGG) laser. Although both lasers share similar mechanisms of action and clinical indications, they differ in wavelength, absorption properties, ablation efficiency, penetration depth, and clinical performance.

### 2.3.2.2 Differences Between Er:YAG and Er,Cr:YSGG Lasers

Both Er:YAG and Er,Cr:YSGG systems belong to the erbium laser family and are widely used for dental hard-tissue applications; however, they differ in wavelength, pulse characteristics, absorption behavior, and clinical interaction profiles (Coluzzi, 2000).

The Er:YAG laser operates at a wavelength of 2.940 nm, which closely corresponds to the peak absorption coefficient of water. Because water represents the primary chromophore in dental hard tissues, this wavelength enables highly efficient photothermal and photomechanical interactions, resulting in precise tissue ablation with minimal thermal diffusion into adjacent structures. Among near- and mid-infrared dental laser systems, Er:YAG demonstrates one of the highest

absorption coefficients in water, which contributes to its high ablation efficiency and superficial interaction profile.

In contrast, the Er,Cr:YSGG laser, operating at 2.780 nm, exhibits strong absorption in both water and hydroxyapatite, although slightly lower than that of Er:YAG in water. As a consequence, both systems are effective for hard-tissue procedures, but their differing absorption characteristics influence penetration depth, thermal interaction, and ablation behavior. Clinically, the higher water absorption of Er:YAG enables faster ablation, shallower cutting depth, and greater precision during enamel preparation, whereas the slightly deeper thermal penetration associated with Er,Cr:YSGG irradiation may provide additional benefits for intracanal disinfection.

Hard-tissue removal with erbium lasers is primarily based on thermomechanical ablation. Laser energy absorbed by water within enamel and dentin causes rapid vaporization and microexpansion, producing micro-explosive effects that facilitate efficient removal of mineralized tissue while minimizing smear-layer formation. In endodontic applications, the stronger water absorption of Er:YAG generally results in superior ablation efficiency compared with Er,Cr:YSGG lasers and promotes enhanced cavitation effects within the irrigant (hydrokinetic effect), thereby improving the removal of debris and contaminants from the root canal system at lower energy densities (Bader & Krejci, 2006; Kokuzawa et al., 2012; J. Wang et al., 2022).

Earlier investigations performed under dry irradiation conditions reported photothermal surface changes characterized by melting or glazing of dentin, which could contribute to partial sealing of dentinal tubules and reduced dentin permeability (Levy et al., 1992). This approach was historically described as conventional laser endodontics. However, contemporary clinical protocols no longer involve irradiation of dry canals. With the use of integrated water–air spray cooling systems, temperature increases during Er:YAG irradiation remain minimal in surrounding tissues (Hubbezoglu et al., 2013; Zan et al., 2016). Current clinical and experimental evidence demonstrates that both erbium laser systems enable selective removal of infected dentin and produce favorable surface morphology without smear-layer formation. In endodontic procedures, maintaining adequate canal hydration and continuous irrigant replenishment throughout treatment is essential to ensure safe and effective laser–tissue interaction (Bader & Krejci, 2006; Vogel & Venugopalan, 2003). Therefore, laser operating mode, pulse duration, and energy parameters must be carefully controlled.

Penetration depth represents another important distinguishing characteristic between these two erbium laser systems. Due to its strong affinity for water, the Er:YAG laser produces highly superficial energy absorption, resulting in limited penetration depth and minimal thermal damage to adjacent tissues. This interaction

profile supports precise cavity preparation and selective caries removal while reducing the risk of injury to surrounding healthy structures.

In comparison, the Er,Cr:YSGG laser demonstrates slightly deeper penetration into dental hard tissues because of its relatively lower water absorption. Consequently, the thickness of the heat-affected layer may be marginally greater; however, when appropriate clinical parameters are applied, thermal effects remain minimal and clinically acceptable. Under these conditions, Er,Cr:YSGG irradiation may also provide cutting efficiency comparable to, or in some cases exceeding, conventional mechanical preparation techniques (Fried et al., 2002; Fattah et al., 2013).

### 2.3.2.3 Clinical Applications

The Er,Cr:YSGG laser operates close to the water absorption peak and therefore shares many clinical applications with the Er:YAG laser due to their similar absorption characteristics (Blanken et al., 2009). Both Er:YAG and Er,Cr:YSGG lasers are widely used in endodontic dentistry. The Er:YAG laser is particularly suitable for cavity preparation, caries removal, enamel conditioning, and dentin surface treatment owing to its high precision and minimal thermal side effects.

The Er,Cr:YSGG laser is effective for both hard- and soft-tissue procedures, including periodontal therapy and soft-tissue surgery. Its ability to achieve hemostasis through controlled ablation is especially valuable in periodontal procedures. Both laser systems enable the selective removal of infected dentin while preserving surrounding healthy structures and are commonly used in laser-assisted endodontic therapy (De Moor et al., 2014; Al-Karadaghi et al., 2015; Arslan et al., 2018; Meire & De Moor, 2024).

Although both erbium lasers can be applied to similar clinical procedures, an important difference between them—besides wavelength—is pulse duration flexibility. The Er,Cr:YSGG laser typically operates with pulse durations of approximately 60, 140, and 700  $\mu\text{s}$ , whereas the Er:YAG laser can operate across a wider range of pulse durations, from very short pulses (e.g., Q-switched nanosecond range,  $\sim 90$  ns) to microsecond pulses (250–700  $\mu\text{s}$ ) and even longer pulses up to the millisecond range (500  $\mu\text{s}$ –10 ms) (Rostan et al., 2001; Alexiades-Armenakas et al., 2008; Brightman et al., 2009). Shorter pulse durations enhance ablation efficiency and reduce thermal diffusion into surrounding tissues (Alexiades-Armenakas et al., 2008), whereas longer pulses improve hemostasis and promote tissue fusion (Çilesiz et al., 1996; Sadony et al., 2024).

The absorption coefficient of the Er,Cr:YSGG laser in water is lower than that of the Er:YAG laser, resulting in slightly deeper penetration depth and therefore a higher energy requirement and longer irradiation time for efficient ablation (Deep et

al., 2021). However, due to its interaction with both water and hydroxyapatite, the Er,Cr:YSGG laser can still achieve effective hard-tissue ablation per pulse, although this may be associated with greater temperature increases if parameters are not carefully controlled (Deep et al., 2021).

## 2.4 Lasers in Endodontic Treatment

### 2.4.1 Conventional Laser Endodontics (CLE)

Early laser endodontic protocols applied laser irradiation *directly* to the dried canal walls after conventional instrumentation. In these methods, a laser fibre was inserted toward the apical region and withdrawn with a *helical* motion so that canal walls and internal micro-anatomy (e.g., dentinal tubules) were exposed to laser light. The intended outcomes were canal wall *debridement* and *decontamination* (Saunders et al., 1995). In addition, morphological modifications of the root canal wall, such as *dentin melting*, *smear-layer removal*, and *tubular sealing* were reported (Levy, 1992). Lasers operating in the visible and near-infrared zones were favoured early on for such re-shaping effects because thin, flexible fibres could negotiate narrow canals (Moritz et al., 1997); mid-infrared systems were also explored using the same “direct irradiation” concept. This body of work is collectively referred to as *conventional laser Endodontics* (Schoop et al., 2002a).

Despite these advantages, several drawbacks were identified. First, achieving uniform wall coverage is difficult for a forward-emitting and, end firing fibre, especially in anatomically complex canals (De Moor et al., 2010). Second, the disinfection outcomes are inconsistent for wavelengths; for example, Nd:YAG (Hardee et al., 1994) and in subsequent reports Er:YAG (Meire et al., 2012). did not consistently achieve satisfactory bactericidal outcome when used in this direct-wall modality. These limitations motivated a transition from direct irradiation of intraradicular dentin to indirect, irrigant mediated activation called as laser-activated irrigation (LAI) (Blanken et al., 2009; De Moor et al., 2010). In LAI, after shaping, the irrigant fills the canal and pulsed laser energy is delivered into the liquid to generate hydrodynamic agitation, thereby enhancing irrigant penetration, debridement and disinfection (Swimberg et al., 2022).

In parallel, clinical protocols continued to emphasize that the mechanical instrumentation remains essential to gain access to the apical anatomy, while irrigation is central to infection control (Fabricius et al., 2006; Violich & Chandler, 2010; Haapasalo et al., 2014). Conventional irrigation has inherent limitations in penetrating complex canal morphologies. To overcome these, activation modes were developed to intensify the irrigant action. As a result, laser gained more recognition as adjuncts in root canal therapy. Nevertheless, debate persists regarding the extent

to which lasers could remove smear layer from entire canal surface (Blanken et al., 2009; Peters et al., 2011). The laser is capable of causing a cavitation effect by vaporizing water leading to ablation in the adjacent tissues. Laser irradiation will purify and decontaminate the root canal structure, leading to open and nearly bacteria-free dentin tubules (Blanken et al., 2009; Peters et al., 2011; Jezeršek et al., 2022).

## 2.4.2 Laser-activated Irrigation (LAI)

Laser-activated irrigation (LAI) has been investigated for several decades as an adjunctive technique to improve the effectiveness of root canal irrigation (De Groot et al., 2009; De Moor et al., 2010; Galler et al., 2019; Matsumoto et al., 2011). Conservative root canal preparation uses manual or mechanically driven instruments, combined with syringe-based irrigant application. This approach primarily addresses the main canal lumen but remains insufficient for cleaning complex secondary anatomical structures. Examples include isthmuses, fins, apical deltas, and lateral canals (Leoni et al., 2017; Siqueira Jr. et al., 1997). As a result, debris and microorganisms may persist within these inaccessible regions despite careful chemo mechanical preparation.

Furthermore, in cases of established endodontic infection, microorganisms are not present merely as planktonic cells. Instead, they are organized into structured multispecies biofilms adherent to the root canal walls (Ricucci & Siqueira Jr., 2010). These biofilms are embedded within a self-produced extracellular polymeric matrix. This structure enhances microbial resistance to antimicrobial agents and mechanical disruption. As a result, conventional irrigation strategies become less effective.

To overcome these limitations, several techniques for irrigant activation have been proposed. These methods enhance irrigant penetration, fluid dynamics, and antimicrobial efficacy within the root canal system (Gu et al., 2009). Approaches include sonic and ultrasonic activation using oscillating intracanal tips and pressure-alternating systems such as multisonic irrigation (Zhang et al., 2019). Pulsed laser-based activation methods are also used. Among these, laser-activated irrigation has attracted increasing attention. This technique can improve irrigant streaming and cavitation effects. As a result, it may enhance debridement and disinfection beyond what conventional syringe irrigation alone can achieve.

### 2.4.2.1 Cavitation

Cavitation represents the principal physical mechanism underlying *laser-activated irrigation (LAI)*. High-speed imaging studies have demonstrated that several laser parameters influence cavitation dynamics, including wavelength, pulse energy,

pulse duration, and fibre-tip geometry (Swimberghe et al., 2022, Robberecht et al., 2023).

LAI generates transient cavitation and acoustic streaming, thereby enhancing the agitation of chelating agents and improving their interaction with root canal walls.

LAI typically employs erbium lasers operating in pulsed mode, with pulse durations ranging between approximately 25 and 250  $\mu\text{s}$  and pulse repetition frequencies of 10–20 Hz. Both erbium laser wavelengths exhibit extremely high absorption in water-based irrigants (De Meyer et al., 2017; Wieliczka et al., 1989). Although their optical penetration depth is limited to only a few micrometres, nearly all delivered laser energy is absorbed within the surrounding liquid. This localized energy deposition results in rapid superheating of a small irrigant volume, causing explosive vaporization and formation of a *primary cavitation bubble*. As the vapour pressure inside the bubble decreases below the external hydrostatic pressure, rapid bubble collapse follows (Blanken et al., 2009; Matsumoto et al., 2011).

These cavitation events occur on a microsecond timescale. The vapour bubbles typically persist for only a few hundred microseconds before imploding, and their collapse is both rapid and forceful, with reported collapse velocities ranging between 5 and 21 m/s, depending on the applied pulse energy (Blanken et al., 2009). Laser-activated irrigation (LAI), including techniques like PIPS (Photon-Induced Photoacoustic Streaming) and SWEEPS (Sub-Wavelength Technology for Enhanced Emission of Photoacoustic Streaming), produces high fluid velocities in the root canal, especially in the apical region, ranging from 1 to 4 m/s (Meire & De Moor, 2024).

Within an irrigant-filled root canal system, the expansion and subsequent collapse of laser-induced cavitation bubbles generate high-velocity fluid motion. This hydrodynamic activity enhances irrigant exchange and promotes the removal of biofilm, dentinal debris, and residual pulp tissue from the canal walls, facilitating their coronal transport out of the root canal system (Deleu et al., 2015; Swimberghe et al., 2022; Robberecht et al., 2023; Meire & De Moor, 2024). Laser-induced vapour bubbles therefore represent a controlled and efficient form of cavitation, defined as the formation and violent implosion of cavities within a liquid following localized energy deposition (Meire & De Moor, 2024). This phenomenon constitutes a powerful mechanism for improving irrigant effectiveness during endodontic treatment.

When sufficient irrigant volume and space are available around the fibre tip, cavitation bubble collapse can occur without mechanical constraint. Under such conditions, bubble implosion generates a transient *shock wave*, characterized by a rapid increase in local pressure (Gregorčič et al., 2012). In addition to primary cavitation, *secondary cavitation bubbles* may form following the collapse of the initial bubble (Matsumoto et al., 2011). These smaller rebound bubbles oscillate for

several hundred microseconds after termination of the laser pulse and further contribute to irrigant agitation within the canal system.

#### 2.4.2.2 Erbium in The Root Canal

The earliest use of lasers in root canal therapy involved irradiating the canal walls after shaping and drying the canal. A laser tip was inserted into the apical region and withdrawn with a helical motion, allowing the laser energy to reach the canal walls and underlying secondary anatomy, such as dentinal tubules, to enhance cleaning and disinfection (Saunders et al., 1995; Meire & De Moor, 2024).

Like any other therapy form, lasers have various limitations for intracanal use. The delivery system for the emitted energy is through the bare optical fibre or different tips. Traditionally, the emission is pointed lengthwise in the axial direction of the tooth and not essentially sideways towards the root canal walls. A spiral motion is needed to better irradiate the canal walls. Hence, it is nearly unmanageable to cover evenly the whole inner part of the endodontic structure by 360° when applying laser irradiation (Sebbane et al., 2022).

#### 2.4.2.3 Erbium in the Pulp Chamber

PIPS/SWEEPS technology, in which the laser tip is typically positioned in the pulp chamber (coronal access opening) filled with any irrigant solution and kept stationary rather than inserted deep into the root canal, is considered safe. This approach minimizes the risk of apical over extrusion of irrigants and helps prevent thermal damage to the root.

#### Photon –Induced Photoacoustic Streaming (PIPS)

The PIPS technique was introduced for clinical applications in 2011 (DiVito et al., 2011) as an advancement of the LAI concept. In comparison to the standard LAI technique, PIPS uses significantly lower pulse energies (10–20 mJ) and very short pulse durations (50 µs) (Peters et al., 2011; Jaramillo et al., 2012; Swimberghe et al., 2022). The laser tip is positioned in the pulp chamber, not inside the canal, which reduces the probability of temperature related harm to the root canal walls and tissues in periapical area (Wen et al., 2021). The mechanism of PIPS is based on inducing intense three-dimensional fluid streaming through rapid oscillation of vapour bubbles. Since the tip remains coronally placed, PIPS avoids direct contact with dentin while still generating vigorous fluid dynamic throughout the canal.

## SWEEPS (shock wave-enhanced emission photoacoustic streaming)

The SWEEPS technique was established to supplementary enhance PIPS efficacy (Yang et al., 2020). SWEEPS uses *paired laser pulses* designed so that the collapse of the primary bubble is accelerated by the arrival of a secondary pressure wave. This accelerates bubble implosion and generates a stronger collapse event capable of enhanced debris and biofilm disruption (Lukač & Jezeršek, 2018). This repeated bubble induced pressure waves through the entire root canal, improving debris removal even in anatomically complex spaces such as isthmuses (Yang et al., 2020).

## AutoSWEEPS

Double-pulse LAI - *AutoSWEEPS* is an advanced automated modality of the Shock Wave Enhanced Emission Photoacoustic Streaming (SWEEPS®) technique, designed for use with Er:YAG lasers in endodontic therapy. It enhances the cleaning and disinfection of complex root canal systems by emitting two sequential laser micropulses with a continuously varying time delay, optimizing the production and effectiveness of acoustic shockwaves within the canal system.

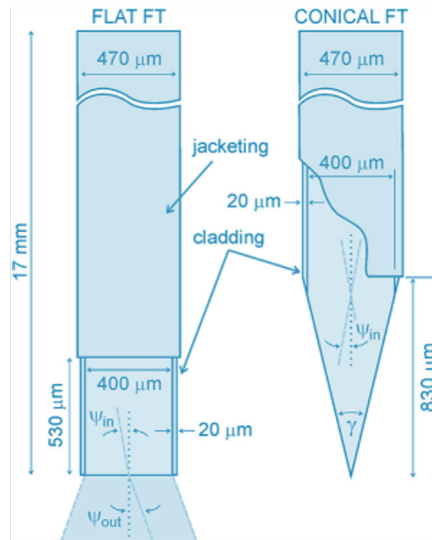
### 2.4.2.4 Fibre Tip Geometry

For laser-assisted irrigation (LAI) applications, two main fibre tip geometries are commonly used: flat and conical. The geometry of the fibre tip significantly affects the pattern of light emission.

In a *conical fibre tip*, light undergoes multiple internal reflections within the tapered end before exiting, **Figure 7**. This leads to two key effects: first, light is concentrated at the very distal end of the cone, producing a high energy density in a small area; second, light exits the tip at a variety of lateral angles.

In contrast, *flat fibre tips* emit light in a largely straight path with minimal lateral spread, typically diverging only 10–15 degrees. As a result, conical tips achieve a higher energy density and a more laterally distributed emission pattern compared to flat tips (George & Walsh, 2009).

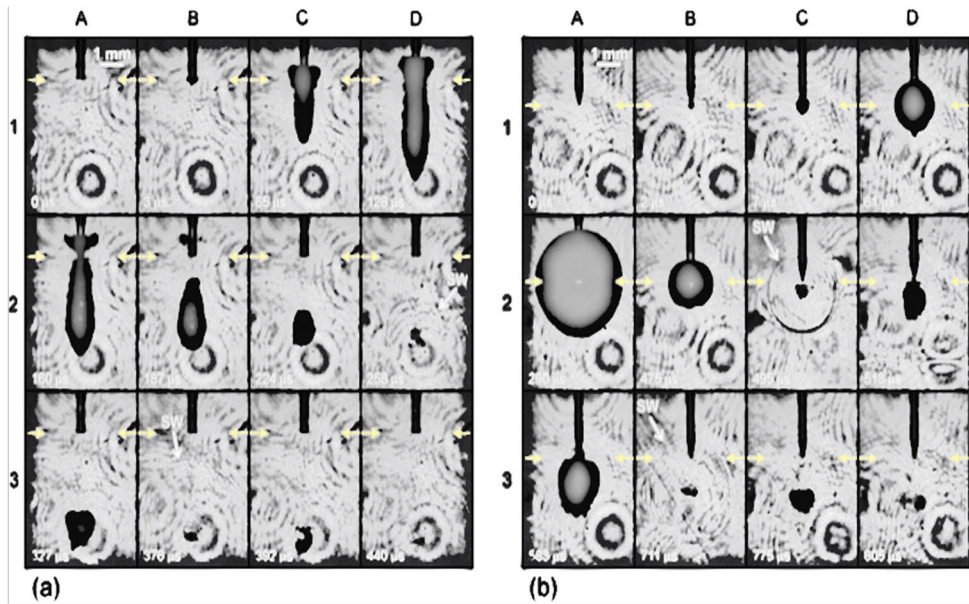
LAI applications mainly utilize two diverse fibre tip configurations: a bare flat-ended fibres (end-firing) and a conical radial firing tip (RFT), **Figure 3**. The laser emission is totally dissimilar to these two fibre types.



**Figure 3.** A flat fibre tip showing more straight forward emission and a conical stripped radial firing tip, which concentrates the energy in the tiny focal point and the energy distribution is more lateral. (modified from Gregorčič et al., 2012)

In a conical radial firing tip, laser energy is concentrated toward the conical end of the fibre and emitted laterally in a 360-degree pattern, resulting in more uniform energy distribution (George & Walsh, 2009). Bare flat tips emit energy primarily forward, with limited lateral dispersion (Meire & De Moor, 2024). Stabholz radial firing tip is typically a  $400\ \mu\text{m}$  or  $300\ \mu\text{m}$  diameter fiber optic tip. Developed by Adam Stabholz and colleagues, these tips are designed for Er:YAG and Er,Cr:YSGG lasers to provide  $360^\circ$  lateral (side-firing) energy emission within the root canal, rather than just forward-directed light. Most clinical studies and technical descriptions specify a  $400\ \mu\text{m}$  or  $300\ \mu\text{m}$  fiber diameter. Some larger "coronal" versions used in related techniques like PIPS (Photon Induced Photoacoustic Streaming) can reach  $600\ \mu\text{m}$ . The tip is modified (often through etching or stripping of the side wall) to emit laser radiation in a *radial/lateral* pattern. These are used for root canal disinfection and smear layer removal, allowing the laser to reach areas that straight-firing fibers might miss. While the "Stabholz tip" often refers to the specific radial-firing design in academic research, several manufacturers produce tips based on these principles for modern dental lasers: Er,Cr:YSGG uses *RFT2* ( $200\ \mu\text{m}$ ) and *RFT3* ( $300\ \mu\text{m}$ ) radial firing tips in various lengths (e.g., 21 mm, 25 mm).

This difference also influences vapour bubble formation: bare tips generate ellipsoidal bubbles, whereas conical radial firing tips form spherical bubbles which expand more symmetrically (Gregorčič et al., 2012), **Figure 4.**



**Figure 4.** The bubble formation for bare tips is shown in Fig. (a), creating ellipsoidal bubbles, whereas conical radial firing tips create bubbles with spherical form Fig. (b). (modified from Gregorčič et al., 2012)

In ideal fluid environments with adequate surrounding space, unrestricted bubble collapse produces powerful shock waves (Gregorčič et al., 2012).

However, in confined spaces like root canals, canal walls restrict bubble size, prolong oscillation time, and reduce peak collapse forces (Matsumoto et al., 2011). Notably, Lukač et al. demonstrated that true shock does not occur within the narrow dimensions of root canals (Lukač et al., 2016). Instead, bubble dynamics create strong negative pressure gradients, facilitating coronal movement of debris (Gregorcic et al., 2016).

#### 2.4.2.5 Comparisons between Er:YAG and Er,Cr:YSGG in LAI

Multiple studies have evaluated LAI using both erbium wavelengths. Although both lasers share similar clinical indications, they differ in absorption characteristics, penetration depth, ablation efficiency, and thermal effects. Despite these differences, several investigations found no noteworthy alterations in smear layer removal between Er:YAG laser and Er,Cr:YSGG in LAI mode (George & Walsh, 2008; De Moor et al., 2010). These suggest that pulse parameters (energy, pulse duration, frequency) may be more relevant to cleaning efficiency than wavelength alone.

The Er:YAG laser demonstrates approximately three times higher water absorption than the Er,Cr:YSGG laser, resulting in shallower penetration and more

localized energy delivery with greater ablation precision. In contrast, the Er,Cr:YSGG laser penetrates deeper into dentinal tissues and may require higher energy levels to achieve comparable ablation efficiency. Studies also indicate that Er,Cr:YSGG lasers can produce greater thermal effects, with dentin surface temperatures reported to be about 30% higher than those produced by Er:YAG lasers, making adequate water cooling essential during clinical use.

Both laser systems effectively remove the smear layer and open dentinal tubules, outperforming conventional irrigation techniques. Laser activation combined with NaOCl and EDTA has shown particularly strong cleaning efficacy, with some studies reporting optimal smear layer removal using Er,Cr:YSGG activation across all canal thirds. Importantly, when applied with recommended parameters and sufficient irrigation, neither laser adversely affects the fatigue strength of root dentin. Additionally, the Er:YAG-based PIPS technique may reduce apical irrigant extrusion due to activation from the pulp chamber rather than deep canal insertion.

#### 2.4.2.6 Clinical Effectiveness of PIPS

The research findings imply that PIPS achieve superior disinfection compared with conventional needle irrigation (CNI), using syringe/needle (Olivi et al., 2014). In a review of 59 PIPS studies, 11 out of 18 disinfection-focused investigations showed that PIPS significantly outperformed CNI (Do & Gaudin, 2020). The superior disinfecting properties were attributed to the highly efficient water and hydroxyapatite absorption of the Er:YAG wavelength, producing robust photoacoustic streaming throughout the entire system (Wen et al., 2021).

PIPS has also been shown to outperform syringe and needle irrigation (SNI), (Irriflex/EndoVac), method with advanced flexible needles and ultrasonic-activated irrigation (UAI) in removing debris in complex canal anatomies (De Moor et al., 2010; Arslan et al., 2014; Lloyd et al., 2014; Deleu et al., 2015). Nevertheless, certain studies were not able to find significant alterations between PIPS and UAI in mandibular molars (Verstraeten et al., 2017), indicating that performance may vary by root morphology.

Earlier laser studies also demonstrated that where CO<sub>2</sub> lasers effectively remove and melt smear layers, Er:YAG lasers are superior for removing residual debris from canal walls (Takeda et al., 1998). Overall, recent evidence indicates that LAI generally provides superior biofilm and calcium hydroxide removal compared with sonic needle irrigation and performs at least comparably—or in some cases better—than ultrasonic activation.

## 2.4.3 Limitations of LAI

### 2.4.3.1 Side Firing Tip of Stabholz

Besides existing advantages, LAI has a few limitations. Stabholz et al. exhibited a newer tip model for application by an Erbium laser device. The laser emission was distributed through a hollow tube, enabling irradiation laterally towards the canal walls more than the usual straightforward emission from the bare ended fibre. The innovative tip model presented a spiral form to fit the shape better. To inhibit unwanted apical extrusion, the tip was closed at its remote end. An SEM study of the laser-treated root canal systems exposed spotless planes without covering debris or smear layer (Stabholz, 2003). Still, thermal side effects potentially harming the periapical tissues are a significant concern. Therefore, strict protection measures should always be observed (Fried et al., 2002; Schoop et al., 2007; Al-Karadaghi et al., 2015).

### 2.4.3.2 Extrusion

Recent laser studies strongly advocate successful new design radial firing tips to ensure coverage of all parts of the endodontic system (Matsumoto et al., 2011). However, when the laser fibre tip is located near to the apex, the direct emission of the laser irradiation could lead to harmful transmission of energy past the apex. This extrusion could have adverse effects on the surrounding tissues and potentially damage the mental foramen or the mandibular nerve, leading to severe pain (Tinaz et al., 2005; George & Walsh, 2008; Boutsioukis et al., 2014; Yost et al., 2015; Doğanay Yıldız et al., 2020; Vidas et al., 2020). A fresh study tested the AutoSWEEPS mode of Er: YAG LAI and could show a greater extrusion of NaOCl compared to the SSP mode. The use of different fibre tips had a significant effect on the amount of extruded irrigant: The PIPS caused the least extrusion, and the SWEEPS caused the highest extrusion of NaOCl, regardless of the LAI modality used (Šnjarić et al., 2025). All these extrusion data for laser, however, are statistically significantly far lower than obtained with conventional needle-syringe irrigation. Earlier the idea of the Stabholz tip was to inhibit this unwanted apical extrusion, the tip was closed at its remote end (Stabholz et al., 2003).

Considering the energetic fluid dynamics in the LAI method, the likelihood of incidental apical extrusion of irrigant must be addressed. Furthermore, tri-dimensional activation during cleaning ought to result in satisfactory penetration in mechanically unattainable zones, avoiding the possible periapical extrusion when considering intracanal laser treatments. The irrigant extrusion, with bacteria and

other organic and in-organic remnants, often sources infection and pain, which can postpone the recovery of surrounding structures (Arslan et al., 2015).

Several investigations have provided valuable insights into the ability of LAI's diverse brands. For instance, reports have revealed that LAI with the Er:YAG laser or the Nd:YAP can lead to added debris extrusion in favour of *Needle Irrigation (NI)* (Arslan et al., 2015; Doğanay Yıldız et al., 2020). Instead, LAI using PIPS fibre tip has been found to result in the minimum periapical extrusion (Vidas et al., 2020). George and Walsh presented their findings on irrigant extrusion with Er,Cr:YSGG LAI, explaining the energy required to drive microdroplets past the apical constriction (George & Walsh, 2008). Yost et al. measured the extrusion of NaOCl under activation with PIPS (10 mJ and 20 mJ). At the same time, another study demonstrated a significant impact on irrigant extrusion when the apical preparation size was altered from ISO 25 to 35 (Yost et al., 2015). Arslan et al. directed a study on irrigant extrusion with PIPS, finding that PIPS, when applied with parameters 0.3 W or 0.9 W, caused a comparable volume of liquid apical extrusion compared with NSI or ultrasonic irrigation (Arslan et al., 2015). Advanced research seeking solutions for these limitations led to the development of radial firing tips (RFT). Conical stripped end in these novel design tips permits the tri-dimensional distribution of laser energy, directed laterally in 360-degree beam, protecting the apical portion (George & Walsh, 2008, 2010; Schoop et al., 2009).

#### 2.4.3.3 Safety

Thermal side effects that potentially harm periapical tissues are a significant concern. Therefore, strict protection measures should always be observed (Al-Karadaghi et al., 2015; Fried et al., 2002; Schoop et al., 2007). Recent laser studies strongly advocate the use of new, successful radial-firing tips to ensure coverage of all parts of the endodontic system (Matsumoto et al., 2011). However, when the laser fiber tip is near the apex, direct laser irradiation can cause harmful energy transmission beyond it. This extrusion could have adverse effects on the surrounding tissues and potentially damage the mental foramen or the mandibular nerve, leading to severe pain (Boutsoukis et al., 2014; Doğanay Yıldız et al., 2020; George & Walsh, 2008; Tinaz et al., 2005; Vidas et al., 2020; Yost et al., 2015).

Conversely, lasers can harm oral tissues and injure ocular tissues if used with the wrong wavelength or power settings. Proper eye protection must be used to avoid harm to ocular tissues. Shiny metal in instruments can also reflect laser light, causing eye injury. High-speed suction is recommended to eliminate all vapors to avoid potential respiratory diseases (Mazhar, 2023).

## 2.4.4 Bactericidal Effect Of Laser Light

### 2.4.4.1 Impact of Wavelength and Thermal Effect

Laser light can inactivate bacteria through photothermal, photochemical, and photomechanical effects, with thermal mechanisms being the most prominent. The bactericidal efficiency depends strongly on the wavelength, as different bacterial components and surrounding media absorb light differently. Near- and mid-infrared lasers (700–1100 nm) primarily induce thermal effects by heating water-rich environments, denaturing proteins, disrupting membranes, and indirectly damaging DNA.

Erbium lasers (e.g., Er:YAG at 2.940 nm, Er,Cr:YSGG at 2.780 nm) are strongly absorbed by water and hydroxyapatite, the main components of dentin. This absorption produces rapid micro-explosions of water within the dentinal tubules, effectively ablating surface layers and disrupting bacterial biofilms. The high absorption in dentin ensures minimal thermal diffusion to surrounding tissues while achieving a potent bactericidal effect, particularly against endodontic pathogens such as *Enterococcus faecalis*. The mechanism is predominantly *photothermal and photomechanical*, with vaporization of intratubular fluid and denaturation of microbial proteins.

*940 nm diode lasers*, in contrast, are poorly absorbed by hydroxyapatite but penetrate more deeply into dentin due to lower water absorption. The bactericidal effect arises primarily from *photothermal heating*, where localized temperatures rise enough to denature bacterial proteins and disrupt membranes within the dentinal tubules. Continuous or pulsed diode irradiation can achieve significant bacterial reduction, although excessive energy may risk thermal damage to the pulp if parameters are not carefully controlled. The diode laser is particularly effective in deeper dentinal layers where erbium lasers have limited penetration.

*Erbium lasers* gain superficial and shallow dentin disinfection with minimal lateral heat, while 940 nm diodes have deep penetration in dentin, being efficiency for residual bacteria in tubules relies on careful thermal management. In practice, combining these lasers can optimize dentin disinfection: erbium lasers remove surface biofilm, while 940 nm diodes target bacteria deeper in the tubules. Both modalities offer a chemical-free, minimally invasive antimicrobial strategy in endodontics and restorative dentistry.

### 2.4.4.2 Clinical Relevance of Laser Disinfection

Thermal inactivation is influenced by laser parameters: higher power density, longer exposure, and pulsed versus continuous-wave modes control the extent of heating

and bacterial kill. Optimizing wavelength and energy delivery allows selective bacterial inactivation while minimizing damage to surrounding tissues or materials. In summary, short wavelengths act via direct molecular damage, while longer wavelengths rely on heat, making laser irradiation a versatile antimicrobial tool.

Various laser systems like CO<sub>2</sub>, Nd:YAG, diode, Er:YAG, and Er,Cr:YSGG have therefore been investigated as adjuncts (Kimura et al., 2000). Diode systems achieved high reductions depending on power settings 86.3% with 1.8 W, while 2.4 W sterilized 98.5% of the tested sections (Berkiten et al., 2000). Comparative experiments across wavelengths (Nd:YAG, the 810 nm diode, the Er:YAG, and the Er,Cr:YSGG) confirmed substantial reductions for *Escherichia coli* or *Enterococcus faecalis* (Schoop et al., 2004; Yasuda et al., 2010; Gutknecht et al., 2016; Asnaashari et al., 2016; Balić et al., 2016) with Er:YAG performing particularly well against *E. faecalis*, at specific settings (Schoop et al., 2004). Importantly, antimicrobial effects were not directly correlated with temperature rise in these settings, supporting the laser assisted protocols when parameters are controlled (Gutknecht et al., 2016; Asnaashari et al., 2016; Balić et al., 2016).

Subsequent diode studies (810 and 940 nm) on extracted teeth emphasized the clinical relevance of treatment modes, showing that additional irradiation even at canal entrances could further lower bacterial counts (Beer et al., 2012). Comparisons of 810 vs 980 nm diode lasers found both wavelengths to significantly reduce *E. faecalis*, with some parameter dependent differences between them (Asnaashari et al., 2016). These findings collectively suggest that diode lasers have good antibacterial potential in endodontic *adjunctive* use, while also highlighting that outcomes depend strongly on wavelength, power, delivery tip design and operational protocols (Rosen et al., 2016, Silva Garcez et al., 2006, Meire et al., 2012).

## 2.4.5 Irrigants in Laser-Activated Irrigation

### 2.4.5.1 Sodium Hypochlorite (NaOCl)

The effectiveness of sodium hypochlorite in laser-activated irrigation depends on both concentration and laser application. Christo et al. evaluated biofilms of *Enterococcus faecalis* in single-rooted extracted human teeth using low NaOCl concentrations with Er,Cr:YSGG laser irradiation. They found that 1% NaOCl delivered via syringe irrigation had significantly higher microbial recovery than 4% NaOCl activated by LAI ( $p = 0.02$ ). Low-power laser activation (0.5 W) did not enhance the antimicrobial effect of low-concentration NaOCl, highlighting the importance of both irrigant concentration and laser parameters (Christo et al., 2016).

Gordon et al. used radial firing tips (RFT) with Er,Cr:YSGG lasers to decontaminate dentin contaminated with *E. faecalis*. They observed a 99.7% reduction in microbial counts after 120 seconds of irradiation, outperforming NaOCl alone. This demonstrates that laser-assisted delivery can amplify the efficacy of irrigants through prolonged exposure and optimized energy settings (Gordon et al., 2007).

Betancourt et al. studied LAI with 0.5% and 5% NaOCl using AFM imaging. Only NaOCl combined with LAI achieved complete eradication of *E. faecalis*, while saline or low-concentration NaOCl alone was ineffective. AFM revealed significant bacterial cell damage when LAI was combined with NaOCl, confirming the synergistic effect of laser activation and chemical irrigants (Betancourt et al., 2019).

#### 2.4.5.2 Chelating Agents: EDTA and Citric Acid

17% EDTA is a widely used chelating agent for eliminating the inorganic component of the smear layer during root canal treatment. When activated with laser systems such as Er:YAG, and Er,Cr:YSGG its effectiveness in smear layer removal and dentinal tubule opening is significantly enhanced, particularly in the apical third of the root canal.

Citric acid (10%) is another effective chelating agent used for smear layer removal. Studies have shown that laser activation improves its efficacy; however, some evidence suggests that citric acid may cause greater dentin erosion and a more pronounced reduction in dentin microhardness compared to EDTA.

Although both solutions demonstrate improved performance when laser-activated, several studies indicate that 17% EDTA may be more advantageous than citric acid in certain situations, particularly because it achieves effective smear layer removal while minimizing dentin erosion (Ozbay et al., 2018).

Masilionyte and Gutknecht compared 940 nm diode laser-assisted irrigation with EDTA versus conventional NaOCl and EDTA or citric acid protocols in root canal therapy. Laser-assisted irrigation allowed reduced chemical usage, fewer intervisit procedures, and accelerated periapical healing. While promising, randomized clinical trials with larger sample sizes are needed for stronger evidence (Masilionyte & Gutknecht, 2018).

Laser activation of these irrigants enhances dentinal tubule patency, thereby improving sealer penetration and potentially contributing to better treatment outcomes.

### 2.4.5.3 Calcium Hydroxide Removal

Calcium hydroxide [Ca(OH)<sub>2</sub>] must be completely removed before obturation to avoid compromising treatment outcomes. Laser-assisted techniques enhance irrigant efficacy for this purpose:

*Photon-Induced Photoacoustic Streaming (PIPS):* Laky et al. compared PIPS, needle irrigation (NI), and sonic activation (SAI) for Ca(OH)<sub>2</sub> removal. PIPS at low power (10 mJ, 15 Hz) achieved near-complete removal without apical extrusion, while high power (25 mJ, 40 Hz) increased extrusion risk. Both laser groups removed significantly more Ca(OH)<sub>2</sub> than NI or SAI (Laky et al., 2018).

*Comparative Study of Multiple Irrigants:* Shi et al. tested conventional needle irrigation (CNI), passive ultrasonic activation (PUI), PIPS, XP-endo Finisher, and EDDY with 3% NaOCl in curved canals. PUI, EDDY, PIPS, and XP removed significantly more Ca(OH)<sub>2</sub> than CNI in apical curves ( $p < 0.05$ ), with no differences among advanced methods (Shi et al., 2022).

*Smear Layer Removal:* Tong et al. evaluated manual dynamic activation (MDA), UAI, SAI, PIPS, and SWEEPS. SEM analysis revealed that PIPS and SWEEPS removed smear layers more effectively in middle and apical thirds of curved canals ( $p < 0.05$ ). Coronal thirds showed no significant differences, indicating laser-assisted irrigants are particularly effective in complex canal anatomies (Tong et al., 2023).

### 2.4.5.4 Biofilm and Irrigant Interaction

Swimberghe et al. demonstrated that Er:YAG LAI enhanced the removal of biofilm-imitating hydrogel in resin models, highlighting the effect of laser activation on irrigant penetration (Swimberghe et al., 2019).

Nagahashi et al. used Er:YAG LAI with different irrigants in pig models. Both coronal and intracanal LAI significantly reduced microbial counts compared to controls. While residual microorganisms remained, LAI improved irrigant efficacy relative to syringe irrigation, confirming that laser activation enhances chemical debridement (Nagahashi et al., 2022).

De Meyer et al. tested LAI with 0.9% NaCl and 2.5% NaOCl in artificial root canal models. LAI achieved  $>1$  log<sub>10</sub> microbial reduction with NaCl and outperformed UAI (0.52 log<sub>10</sub>) and SI ( $<0.25$  log<sub>10</sub>). With 2.5% NaOCl, LAI and UAI were equally effective, illustrating that laser activation can significantly boost low-potency irrigants and maintain strong efficacy with standard concentrations (De Meyer et al., 2017).

## 2.4.6 LAI vs. Ultrasonic-activated Irrigation (UAI)

Laser-activated irrigation (LAI) and passive ultrasonic irrigation (PUI/UAI) are commonly used as adjuncts to conventional endodontic therapy to enhance canal disinfection and debris removal. However, the antiseptic effectiveness of LAI combined with low-concentration sodium hypochlorite (NaOCl) remains less widely recognized.

Betancourt et al. (2019) evaluated the antimicrobial efficacy of different irrigation protocols against *E. faecalis* using atomic force microscopy (AFM). Complete bacterial elimination was achieved only with 5% NaOCl and 0.5% NaOCl combined with LAI, whereas 0.5% NaOCl alone and saline without laser activation were ineffective. PUI showed limited antibacterial impact compared with LAI. AFM imaging also demonstrated significant surface alterations in bacterial cells following NaOCl + LAI treatment, indicating enhanced disinfecting ability. These findings suggest that Er,Cr:YSGG-assisted LAI significantly improves the antimicrobial action of low-concentration NaOCl.

Removal of intracanal medicaments such as calcium hydroxide ( $\text{Ca(OH)}_2$ ) before obturation is essential to prevent adverse treatment outcomes. Laky et al. (2018) compared needle irrigation (NI), sonic activation (SAI), and photon-induced photoacoustic streaming (PIPS). Both low-power and high-power PIPS settings achieved significantly greater  $\text{Ca(OH)}_2$  removal than NI and SAI. However, the high-power mode increased apical extrusion risk, whereas low-power PIPS achieved near-complete removal without extrusion, supporting its clinical safety and effectiveness.

Similarly, Shi et al. (2022) compared conventional needle irrigation (CNI), PUI, PIPS, XP-endo Finisher, and EDDY systems for  $\text{Ca(OH)}_2$  removal in S-shaped canals using 3% NaOCl. While all techniques removed  $\text{Ca(OH)}_2$  from straight and curved canal segments, PUI, PIPS, EDDY, and XP-endo Finisher were significantly more effective than CNI in apical curvature regions, with no significant differences among the activated techniques.

Calcium hydroxide [ $\text{Ca(OH)}_2$ ], a pharmaceutical extensively utilized as an intervisit remedy, must be entirely cleaned out from the endodontic system prior to obturation to exclude undesirable consequences regarding the therapy. PIPS was investigated against NI and sonic activation (SAI). Protection concerns related to apical extrusion were even focused. The test groups were allocated to NI, sonic device irrigation, and PIPS, either with a lesser power mode (10 mJ, 15 Hz) or an upper power setting (25 mJ, 40 Hz). Irrigation with needle and sonic-supported elimination ended in meaningfully lower  $\text{Ca(OH)}_2$  eradication compared to the two laser groups, having pointedly added  $\text{Ca(OH)}_2$  deletion in the ultrasonic group related to that in the needle irrigation group. Concerning apical extrusion, the upper power mode (25 mJ, 40 Hz) group caused a noteworthy greater colour alteration in

the test using the periapical gel compared to the other groups. PIPS applied with the lower power mode (10 mJ, 15 Hz) attained nearly comprehensive eradication of  $\text{Ca}(\text{OH})_2$ , not causing apical extrusion of the irrigants (Laky et al., 2018).

An experiment by Shi et al. assessed the success of conventional needle irrigation (CNI), passive ultrasonic activation (PUI), photon-induced photoacoustic streaming (PIPS), XP-endo Finisher (XP), and EDDY to eradicate calcium hydroxide in curved canal areas. For irrigation, 3% NaOCl was used. The residual  $\text{Ca}(\text{OH})_2$  was detected by digital imaging. All the examined methods could totally eradicate  $\text{Ca}(\text{OH})_2$  in 100% of cases from the curved and straight parts of the tested S-shaped root canal. Concerning the apical curve, PUI, EDDY, PIPS, and XP were able to move a meaningfully more significant amount of  $\text{Ca}(\text{OH})_2$  compared to CNI ( $P < 0.05$ ), having negative meaningful alterations between all tested sample units ( $P > 0.05$ ). CNI showed meaningfully minor efficiency related to other tested methods (Shi et al., 2022).

#### 2.4.7 Bactericidal Effect of Laser Light

Microbial contamination of the root canal system is the primary etiological factor responsible for the progression of pulpal and periapical lesions (Bergenholtz, 1974; Fabricius et al., 1982; Fabricius et al., 2006). Achieving an irritant-free canal environment through biomechanical instrumentation is therefore essential; however, its effectiveness is substantially limited by the presence of the smear layer and the complex anatomical morphology of the root canal system, making complete cleaning a formidable challenge (Sjögren et al., 1990). The smear layer formed during instrumentation consists of a superficial coating approximately 1–2  $\mu\text{m}$  thick, with an underlying layer penetrating up to 40  $\mu\text{m}$  into the dentinal tubules (Mader et al., 1984).

Current strategies for eliminating microbial and instrumental residues involve chemical, ultrasonic, and laser-assisted methods, yet no single technique alone can ensure complete disinfection throughout the canal system. Commonly employed irrigants, such as sodium hypochlorite (NaOCl) and ethylenediaminetetraacetic acid (EDTA), are crucial for debris removal and smear layer elimination (Peters et al., 2011). The smear layer was first identified and characterized using scanning electron microscopy (SEM) with electron microprobe analysis by Eick et al. in 1970 (Violich & Chandler, 2010). Subsequent SEM studies by Brännström and Johnson in 1974 reported a thin layer of crushed dentin remnants, approximately 2–5  $\mu\text{m}$  thick, extending into dentinal tubules (Violich & Chandler, 2010). McComb and Smith (1975) were the first to designate this layer as the smear layer following endodontic instrumentation, while Pashley et al. (1988) demonstrated that smear layer particles

become burnished onto dentin surfaces, making them resistant to conventional irrigation.

The smear layer comprises both organic and inorganic components, including viable microorganisms and necrotic tissue remnants, and it can act as a physical barrier that limits the penetration of chemical disinfectants into dentinal tubules (Swimberghe et al., 2019; Liu et al., 2022). Biofilms are often present in more complex anatomical regions, such as anastomoses and bi-canal, further challenging complete disinfection (Zehnder et al., 2005; Nagahashi et al., 2022). Peters et al. (2001) reported that over 35% of canal wall surfaces may remain untouched even after preparation with four different nickel–titanium (NiTi) systems, highlighting the limitations of mechanical instrumentation alone.

Most existing intracanal medicaments have a limited antimicrobial spectrum and insufficient penetration into dentinal tubules, leaving microorganisms beyond the reach of conventional chemo-mechanical procedures (Jaramillo et al., 2012). Microorganisms embedded in biofilms are encased in a self-produced extracellular polymeric matrix, rendering them particularly resistant to irrigants (Tanaka et al., 2021). Effective disinfection, therefore, requires strategies that enhance irrigant penetration and activation within the canal system.

Laser-assisted irrigation (LAI) has emerged as a promising adjunctive approach for both deep cleaning and deep disinfection. Studies have demonstrated that LAI can achieve superior biofilm removal compared to conventional needle irrigation (CNI) or ultrasonically activated irrigation (UAI) in artificial biofilm models (De Moor et al., 2010; Ayar et al., 2015), although results are not entirely consistent, with some studies showing no significant difference between CNI and LAI (Christo et al., 2016). Dentinal tubules exhibit an S-shaped morphology in the coronal region and a straighter trajectory in the radicular portion, allowing microorganisms to penetrate deeply—up to half the tubule length and extending toward the cemento-dentinal junction—where they are protected from conventional irrigation (Torabinejad et al., 2002). These observations underscore the necessity for techniques that enable irrigants and laser energy to reach and eliminate bacteria in these deep areas.

Several lasers commonly used in dentistry, including argon, diode, Nd:YAG, Er:YAG, and Er,Cr:YSGG, can transmit energy via thin optical fibers or specialized delivery systems into root canal spaces. The Er:YAG laser, particularly when used with photon-induced photoacoustic streaming (PIPS), has shown remarkable efficacy. Jaramillo et al. (2012) reported that PIPS combined with 6% NaOCl for 20 seconds achieved 100% inhibition of *Enterococcus faecalis* in infected canals, whereas PIPS with phosphate-buffered saline achieved only 50% inhibition. Similarly, De Meyer et al. (2017) demonstrated that LAI using 0.9% NaCl reduced bacterial counts more effectively than UAI or syringe irrigation, with NaOCl further

enhancing biofilm reduction, though differences between irrigation methods were less pronounced when NaOCl was employed.

Other adjunctive irrigation activation methods, such as passive ultrasonic activation (PUI), XP-endo Finisher, and EDDY, have also been evaluated for their ability to remove calcium hydroxide from curved canals. Shi et al. (2022) showed that all these methods achieved complete removal in straight and curved S-shaped canals, with PUI, EDDY, PIPS, and XP outperforming conventional needle irrigation, particularly in apical curves. Similarly, studies comparing CO<sub>2</sub> and Er:YAG lasers demonstrated that while CO<sub>2</sub> lasers can melt and remove smear layers, Er:YAG lasers are superior in eradicating residual debris from canal walls (Takeda et al., 1998b).

Advanced laser technologies, including PIPS and shock wave enhanced emission photoacoustic streaming (SWEEPS), have further enhanced smear layer removal. Tong et al. (2023) demonstrated that these methods achieved superior cleaning in the middle and apical thirds of curved root canals compared to manual dynamic activation, UAI, and sonically activated irrigation, while no differences were observed in the coronal third.

Finally, the bactericidal effect of lasers has been confirmed across various wavelengths. Comparative studies using Nd:YAG, 810 nm diode, Er:YAG, and Er,Cr:YSGG lasers have shown significant reductions in *Escherichia coli* and *Enterococcus faecalis*, with Er:YAG performing particularly well against *E. faecalis* under controlled settings (Schoop et al., 2004; Yasuda et al., 2010; Gutknecht et al., 2016; Asnaashari et al., 2016; Balić et al., 2016; Cheng, Tian et al., 2017; Cheng, Xiang et al., 2017). Notably, these antimicrobial effects were not directly associated with temperature increases, supporting the safety and efficacy of laser-assisted protocols when parameters are properly managed.

Jaramillo et al. examined the Er:YAG laser operating by PIPS tip with *E. faecalis* diseased root canals. Laser usage was accomplished for 20 seconds with 6% NaOCl, while phosphate-buffered saline (PBS) was used in the comparison. Additionally, dentinal debris was formed besides colony-forming units. Combining 20 seconds of laser irradiation using PIPS with 6% NaOCl presented 100% inhibition of *E. faecalis* growth, related to a 50% inhibition when combining PIPS with PBS. Therefore, PIPS technology is a meaningful technique for eliminating *E. faecalis* from the contaminated endodontic structure (Jaramillo et al., 2012).

In conclusion, while mechanical instrumentation combined with chemical disinfection remains fundamental, achieving deep cleaning and disinfection requires adjunctive strategies capable of overcoming the anatomical complexities, smear layers, and biofilm resilience within the root canal system. Laser-assisted irrigation, particularly using Er:YAG-based technologies, provides a powerful tool to enhance microbial eradication, smear layer removal, and overall endodontic success. To

achieve ideal cavitation effectiveness in LAI, erbium lasers with conical fibre tips should be applied and operated at the shortest possible pulse durations combined with high pulse energy output (Meire et al., 2024).

# 3 Aims

This study series aimed to evaluate the efficacy of laser-assisted endodontic treatments in deep cleaning. The expanding interest in laser-assisted endodontics underscores the importance of evaluating these technologies from a combined viewpoint that considers not only their cleaning capabilities but also their impact on dentin bonding and structural durability. A systematic approach that links irrigation effectiveness, adhesive performance, and dentin fatigue behaviour is therefore critical to establishing the true clinical viability of erbium laser applications in endodontics. Using manufacturers' protocols, both commonly used erbium lasers, Er:YAG and Er,Cr:YSGG, were analysed with conventional bare-ended tips and novel conical radial-firing tips (RFT), and the 940nm diode with an endodontic tip.

The specific aims of the studies were:

- I. To assess the efficacy of the laser in smear layer removal with Er:YAG (2.940 nm) laser using PIPS (photon-induced photo acoustic streaming) in root canals related to LAI (laser- activated irrigation) (Study I).
- II. To determine whether Er:YAG (2.940 nm) and Er,Cr:YSGG (2.780 nm) laser exposer by new-type of glass-fibre tips would enhance the intra-radicular bonding of fibre posts. The tested null hypotheses were that irradiation protocols composed by lasers with modified tips would have no effect on (1) the push-out bond strength or (2) the interfacial interaction of luted fibre posts to intraradicular dentin (Study II).
- III. To detect potential alterations of the flexural strength (FS) and fatigue resistance, and the surface morphology of root dentine following laser-assisted endodontic protocols using (Er:YAG, Er,Cr:YSGG, and 940 nm diode). The tested null hypotheses were as follows: (1) laser irradiation using Er:YAG, Er,Cr:YSGG, and 940 nm diode protocols does not affect the 4-point FS of root dentine, and (2) laser irradiation does not affect fatigue resistance of root dentine, and (3) the laser irradiation does not alter the surface morphology of dentine (Studies I, II, III).

## 4 Materials and Methods

### 4.1 Materials

A total of one hundred and thirty (130) single-rooted teeth extracted during routine dentin treatments were used in these series of studies. In accordance with local regulations (Tissue Act 20), the use of anonymized teeth obtained as clinical waste material is exempt from the requirement of ethical approval. After extraction, the teeth were stored at 4°C in 0.9% sodium chloride containing 0.02% sodium azide (NaN<sub>3</sub>) to inhibit microbial progress. The teeth were used within three months of extraction to ensure tissue integrity.

#### 4.1.1 Root Canal Treatment w/o Obturation (Studies I, II)

For the root canal treatment (Study I), the access cavities were prepared using a traditional diamond bur (Horico, Berlin, Germany) to ensure efficient cutting of tooth structure and removal of existing restorative materials, particularly amalgam. For study I, thirty (30) teeth were prepared following conventional endodontic access principles to expose the canal orifices. For Studies II and III, forty (40) extracted teeth were decoronated 1mm above cemento-enamel junction. Canal patency and working length were customized using a K-File 15 file.

To simulate clinical conditions, the teeth were stabilized in dental putty during subsequent root canal treatment. Primary canal shaping was performed using reciprocating files (WaveOne, Dentsply, Sirona, Charlotte, NC, USA) up to size #45 respecting the working length (Study II) and further enlarged for final standardization in upper incisors up to ISO 90, canines up to ISO 70, and premolars up to ISO 60 (Hedström, Henry Schein, Germany) (Study I). Irrigation with 3 ml of 0.9% NaCl solution was used between the files. No commonly used irrigants (EDTA, CHX, NaOCl) were used since the aim was to focus on the novel conical laser tips' capability to eradicate the smear layer.

#### 4.1.2 Dentin-post Disc Preparation (Study II)

After root canal instrumentation, paper points #45 (Dentsply Maillefer, Ballaigues, Switzerland) were used for drying the root canals, and the lateral condensation technique was utilized for obturation with gutta-percha points, applying a resin-based sealer for root canals (AH Plus, Dentsply DeTrey, Konstanz, Germany). For sealing the canal orifices, a resin-modified glass-ionomer cement (Vitremer, 3M Oral Care, St Paul, MN, USA) was applied, and to guarantee the setting of the endodontic sealer, all samples were deposited in 100% humidity for seven days at 37°C.

#### 4.1.3 Dentin Beam Preparation (Study III)

Forty (40) extracted caries-free roots were decoronated and sectioned to obtain 148 dentin beams (0.9×0.9×12mm) by a water-cooled low-speed saw (Isomet, Buehler, Lake Bluff, IL, USA). For the quasi-static testing, an online calculator was applied for constant data (sealedenvelope.com), based on flexural strength values described by Ryou et al. (2011) for sound deep and superficial dentin (119 ± 31 MPa vs. 169 ± 28 MPa), assuming 95% power and a 1% level of significance. For fatigue testing, sample size estimation was derived from former *in vitro* investigations assessing dentin fatigue strength under comparable investigational environments (Stape et al., 2022).

Beam preparation was partly adopted and modified from Staninec et al. (2009) with the pulpal surfaces lightly wet-polished by hand using 320-grit SiC grinding paper (Carbimet & Microcut, Buehler Ltd) for 10 seconds to standardize dentin and smear-layer thickness. Before testing, all specimens were re-inspected using 40× magnification under a stereomicroscope (Leica M60), then stowed in purified water at 37 °C. Samples presenting noticeable flaws were excluded and replaced. The final dentin beams were randomly assigned into the laser irradiation group or the control group (Study III).

#### 4.1.4 Laser Treatment

Laser irradiation protocols for different lasers used in current studies are presented in **Table 2**. Protocols followed respecting manufacturer's recommendations.

**Table 2.** Laser irradiation protocols used for studies I–II–III.

Laser	Wavelength	Tip	Firing	Protocol	Time	Study	Manufacturer
Er:YAG	2940 nm	PIPS	Radial	20 mJ, 15 Hz, 0.3 W, 50 µs (SSP)	2×30 s	I	Lightwalker, Fotona Ljubljana, Slovenia
					120 s	II	
					4×20 s	III	
		Preciso	End	40 mJ, 12 Hz, 0.45 W, 100 µs (MSP)	4×5–8 s	I	
4×20 s	II						
Er,Cr:YSGG	2780 nm	RFT3	Radial	2.25 W, 50 Hz H, Air 35, Water 25	4×20 s	II–III	Waterlase, Biolase, San Clemente, USA
		MZ4	End	2.5 W, 75 Hz H, Air 20, Water 40	4×20 s	II	
Diode	940 nm	200µm	–	1 W, CW	4×20 s	III	Epic X, Biolase, San Clemente, USA

**4.1.4.1 Photon Induced Photoacoustic Streaming PIPS (Study I)**

After completion of root canal preparation and intermediate rinsing, the specimens were randomly assigned to three experimental groups: 1) PIPS group: specimens were irradiated using the PIPS protocol at 20 mJ, 15 Hz, 0.3 W with a pulse duration of 50 µs (SSP mode). Irradiation was performed for 30 seconds in the presence of NaCl solution only, not using EDTA or NaOCl. The procedure was repeated twice. The laser tip was placed passively within the pulp chamber, near to the canal openings, without entering the canal space and continuously rinsed with 2ml of irrigant to uphold hydration by a handheld syringe with a 25-gauge needle positioned above the laser tip in the coronal side of the canal orifice. 2) Preciso (RFT) group: specimens were irradiated with parameters of 40 mJ, 12 Hz, 0.45 W and 100 µs pulse duration (MSP mode). The application consisted of four cycles of helical withdrawal movements, each lasting 5–8 seconds depending on the canal length. Irradiation commenced 1mm from of the apical opening and proceeded coronally throughout each cycle. Both laser groups received rinsing with 0.9% NaCl in between irradiation cycles. Control group: the control specimens did not receive laser irradiation. Instead, canals were irrigated with NaCl solution following every ISO file size during instrumentation to match the fluid dynamics exposure of the experimental groups.

#### 4.1.4.2 Laser Irradiation for Intraradicular Bonding (Study II)

The second study compared the cleaning effect of Er:YAG with PIPS (radial firing tip) and Preciso (bare fibre tip), and Er,Cr:YSGG with RFT (radial firing tip) and MZ4 (bare fibre tip). The control group was not exposed to laser irradiation. The sample preparation followed the same procedure as in Study I.

#### 4.1.4.3 Fatigue Strength (Study III)

Root dentin beams were randomly assigned to four groups (n=37/group) following the laser type, mode of operation, and laser tip configuration (Table 2). To simulate clinical conditions, a custom mold was fabricated to simulate root canal environment, providing space for four beams, **Figure 5**. Beams from four different teeth were positioned in the mold and irradiated simultaneously on the pulpal surface whilst submerged in 0.9% NaCl. All procedures followed the manufacturer's recommended irradiation protocols for respective laser delivery tips. Pulse energies varied among for differences in tip diameter, enabling comparable fluence across systems.

- *The Er:YAG 2.940 nm group* (Lightwalker, Fotona, Ljubljana, Slovenia) followed the protocol at Table 2. A quartz PIPS tip with 0.4 mm in diameter and 12mm long, was utilized. The tip was placed in the pulp chamber near to the canal openings of the NaCl-rinsed root canal and held unmoved. During the laser exposers cycles, 4×20 seconds, the beams were continuously rinsed with 2 ml of irrigant to uphold hydration by a handheld syringe with a 25-gauge needle positioned above the laser tip in the coronal side of the canal orifices, correspondingly to the protocol above. For the photon-induced photoacoustic streaming, the canal must always be kept wet.

- *The Er,Cr:YSGG 2.780 nm laser group* (Waterlase, Biolase, San Clemente, USA) was irradiated with parameters of 2.25 W, 50 Hz, H mode (60 μs) and pulse air 35%+ 25% water using a radial firing RFT3 tip, diameter 0.3mm. The tip was positioned respecting the working length and irradiated at a speed of 2 mm/s up to the upper part of the mold. The procedure was completed four times, 10 seconds with approximately 10 seconds intervals in between every laser exposers, for 4×20 seconds cycles.

- *The 940 nm diode laser group* (Epic-X, Biolase, San Clemente, USA) was lased at 1W, continuous wave (CW), with an endo tip having a diameter of 0.2 mm, employing the same protocol as the Er,Cr:YSGG group above except in a dry canal.

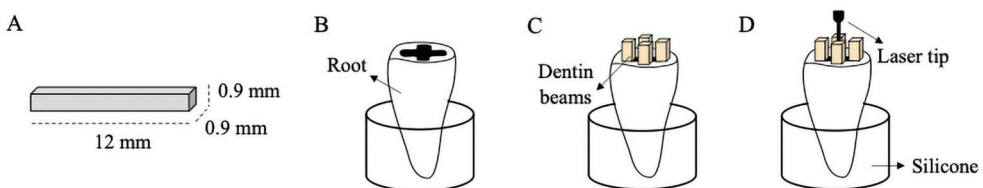
- *The Control group* was irrigated with 5 ml NaCl-solution by a 25-gauge needle. A laser fibre tip with 0.3 mm was positioned in the middle part of the mold in working length and stirred in rotating movement upwards 4 times respecting intervals and irrigated with 5 ml NaCl-solution in between and following all four

“cycles”. This procedure was completed without laser exposer but to imitate the possible chance of the fibre tip touching the beam surface during the helicoidal movement and the potential following influence on fatigue behaviour throughout the fibre tip movement, even with no laser exposer.

Throughout all protocols, the beams were handheld kept unmoved to inhibit any motion caused by the LAI cavitation outcome.

The differentiation in these procedures lies on that Er:YAG with PIPS was positioned only in the pulp cavity, while Er,Cr:YSGG, and diode tips were placed inside the canal. The laser irradiation is absorbed in the liquid, in this test set-up, NaCl-solution in both erbium groups; meanwhile, the protocol with diode laser was dry. It is to alert that pulse energies are different to compensate for diverse glass tip diameters, depending on the laser system, to attain a comparable fluence. H mode is 60  $\mu$ s pulse duration. The applied energy densities were as follows: diode 60 J/cm<sup>2</sup>, Er:YAG PIPS 18 J/cm<sup>2</sup>, and Er,Cr:YSGG RFT3 135 J/cm<sup>2</sup>.

The control group comprised beams without laser irradiation, rinsed with only a solution of 0.9% saline solution. EDTA is a widely used for the chelating properties for eliminating the smear layer in endodontic treatments. Nevertheless, the current study did not apply smear layer eradicating irrigation solutions. The goal was to separate the influence of irrigants in laser-assisted endodontic therapy on the topography of the dentinal surface, and to concentrate exclusively on the outcome of laser irradiation on fatigue behaviour. Whereas saline solution was the sole irrigant for erbium laser or control groups, the 940 nm diode group received saline solution rinse following each laser irradiation. Treatment protocols used followed the manufacturer's recommendations for corresponding devices. The buccal surfaces of all dentin beam were signed to designate the laser irradiation received side for SEM orientation.



**Figure 5.** Protocol arrangement. **(A)** beam preparation of root dentin; **(B)** mold mimicking the root canal situation; **(C)** dentin beams placed inside the root; **(D)** laser treatment on the inner pulpal side of the beams (*from study III*).

## 4.2 Research Methods

### 4.2.1 SEM Analysis – Smear Layer Removal (Study I)

After to instrumentation and laser exposer, the teeth were stowed in NaCl and 1% thymol and split lengthwise for accurate SEM analysis. The coronal portion was detached by the dento-enamel junction with a diamond disc (Horico, Germany). All specimens were fixed in 3% glutaraldehyde buffer liquid, then underwent a graded ethanol series for dehydration, and subsequent air-drying. Lastly, five teeth from all groups were inspected under a microscope to be selected for SEM evaluation. Since different parts of the root canal, like dentinal tubule openings, canal walls, and extension, gather dentinal debris during mechanical instrumentation, eradicating this substance will be analysed under significant magnification. All specimens underwent inspection in a traditional high vacuum in the SEM. The sample roots were scanned separately by respective specimens in all three sections: coronal (3mm from canal opening), middle, and apical (3mm from apex).

The residual quantity of a smear layer on the canal walls was recorded, and the evaluation was made by following *the Hülsmann's score*:

*Score 1: dentinal tubules completely open*

*Score 2: more than 50% of dentinal tubules open*

*Score 3: less than 50% of dentinal tubules open*

*Score 4: almost all dentinal tubules are covered with a smear layer (Study I)*

### 4.2.2 Intraradicular Bonding (Study II)

#### 4.2.2.1 Post Space Preparation and Fibre-Post Cementation

A specific fibre post method (3M RelyX Fiber Post Drill, 3M ESPE), size #3 (1.9 mm in diameter), was applied using low speed, respecting a penetration of 13 mm, leaving a 5 mm thick endodontic filling as an apical seal. Root canals were standardized with similar enlargement preparations, as described earlier. The prepared post-space was rinsed with a generous amount of distilled water. Specimens were randomly shared into five groups (n=8) following the respective laser type and mode of operation, **Table 2**. The control group did not receive laser irradiation but was irrigated with saline solution. Experimental groups involved two erbium lasers: (1) (Er:YAG, Lightwalker, Fotona, Ljubljana, Slovenia) and (2) (Er,Cr:YSGG, Waterlase, Biolase, San Clemente, CA, USA). Laser irradiation was used in root canals filled with NaCl solution, testing each device's two distinctive tips (end-firing

and radial-firing), respecting specific fabric protocols for different firing tips used in laser-assisted endodontics, **Table 2**.

Fibre posts (RelyX Fiber Post, 3M ESPE) size #3 were primarily sanitized using 70% alcohol following air-drying for 30s. Post surfaces were Silane (RelyX Ceramic Primer S, 3M ESPE) treated with disposable applicator brushes for 60 seconds. After 5 minutes (manufacturer's recommendation), when the solvent was evaporated, paper points (Dentsply Maillefer) were used to eliminate extra humidity from the root canals. A self-adhesive resin cement (U200, 3M ESPE) was injected with precaution inside the root canal from the apical to the cervical portion, operating with single-use auto-mix endo tips to reduce slot development. The extra cement was cleaned after inserting the fibre post into the root canal. The post was manually kept stable by employing compression for 2 minutes, as in clinical situations. The post was light-cured 5 minutes later by an LED unit (Elipar Deepcure, 3M ESPE) at  $1.400 \text{ mW/cm}^2$  for 90 seconds. Afterwards, all the samples stayed preserved in 100% relative humidity at  $37^\circ\text{C}$  for seven days.

#### 4.2.2.2 Micro Push-out Bond Strength Testing (*Study II*)

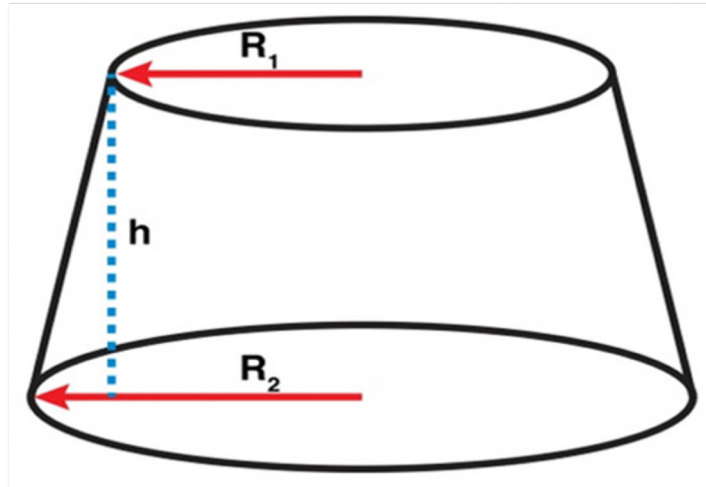
Custom-made molds were made, and roots were embedded in epoxy. Root lengths were taken to 18 mm. Roots were sectioned horizontally in nine (three cervical, three middle, three apical thirds) approximately 1mm thick slices operating under water-cooling with a slow-speed diamond saw (Isomet, Buehler). After coding root sections, a stereomicroscope (Leica M60, Leica Microsystems, Wetzler, Germany) at  $40\times$  magnification was applied to measure coronal and apical radiuses of fibre posts. Image J software (National Institutes of Health, Bethesda, MD, USA) was utilized to determine the coronal and apical post radius. A common testing machine (Autograph AGS-X, Shimadzu, Kyoto, Japan) at 0.5 mm/min, with cylindrical plungers of stainless steel, compatible with post dimensions, was used to subject posts to loading under compression in the apical-coronal trajectory. A blinded operator implemented the push-out test. The plungers were placed in a way to have a contact on the surface of the post merely. The distribution of the push-out load was continued until the occurrence of debonding, indicated by the extrusion of the post and a quick fall inside the load-displacement graph. The maximum failure load was recognized in N. The value was applied to determine the push-out bond strengths, recorded in MPa, for all root sections using the subsequent *formula*:

*Push-out bond strength (MPa) = Maximum Load (N) / Adhesion surface area (mm<sup>2</sup>),*

**Figure 6.**

The adhesion surface area (SA) was calculated as

$$SA = (\pi r_1 + \pi r_2) \times \sqrt{h^2 + (r_1 - r_2)^2}$$



**Figure 6.** Surface area (SA),  $r_1$  is the smaller post radius (mm),  $r_2$  is the larger post radius (mm),  $h$  is the thickness of the root section (mm). "Maths at Your Fingertips" Play Store.

#### 4.2.2.3 Fracture Patterns

The fractured samples were analysed by a blinded-calibrated operator under a stereomicroscope (Leica M60, Leica Microsystems) with magnification range of 10–40× to determine *failure types*:

- (I) adhesive failure between post and resin cement;
- (II) adhesive failure between resin cement and dentin;
- (III) mixed failure with resin cement covering part of the post surface;
- (IV) cohesive failure within the fibre post and (V) cohesive failure of dentin.

#### 4.2.2.4 Nanoleakage

For qualitative interfacial nano leakage evaluation, three roots ( $n=3$ ) from every group underwent random bonding and cutting into discs, as explained before. Nano leakage was utilized to estimate the integrity of the bonded interface by quantifying the uptake of silver nitrate. The nano leakage evaluation was conducted following a protocol formerly portrayed by Tay et al. (2007). Shortly, slices underwent wet-polishing with 2000-grit SiC paper and received dual coatings of nail varnish to a layer equal to 1 mm of bonded interfaces. Slices were rehydrated in distilled water

for one hour, immersed for 24 hours into 50% (w/v) ammoniacal silver nitrate (pH 9.5), and rinsed throughout in distilled water for 120 seconds. Samples were then immersed into a photo-developing solution (Kodak Professional D-76 developer, Kodak, Rochester, NY, USA) for 8 hours underneath fluorescent light to diminish silver ions into metallic silver grains inside the water-filled gaps alongside the bonded interface. After being enclosed in epoxy resin, the discs were wet-polished with 600-, 1000- 2000-grit SiC paper (Carbimet, Buehler) and 1, 0.25 (MetaDi, Buehler) and 0.05  $\mu\text{m}$  (MasterPrep, Buehler) polishing pastes. Specimens trailed all polishing steps, ultrasonic-cleaning in distilled water, air-drying for 2 hours, stub-mounting, silica-drying overnight, and carbon-sputtering. An experienced blinded operator evaluated nano leakage elongations by means of SEM imaging by backscattering mode at 10 kV (Phenom ProX, Phenom-World, Eindhoven, The Netherlands). Elongations with silver uptake and nano leakage patterns were examined at 3,000 $\times$  to 10,000 $\times$  magnifications.

## 4.2.3 Microscopic Evaluation of the Surface and Bonding Interface (Studies II-III)

### 4.2.3.1 SEM Characterization of Intraradicular Bonded Interface (Study II)

For bonded interfacial characterization under SEM, two supplementary roots (n=2) from every group underwent random bonding and sectioning to discs, as described earlier. Discs were inserted in epoxy resin and wet-polished with SiC papers of 600, 1200-, 2000- and 4000-grit, and paste-polished with 1, 0.25, and 0.05  $\mu\text{m}$  (Buehler) coarseness. Following all polishing steps, samples were cleaned in ultrasonic device for 3 minutes within distilled water. Bonded interfaces were applied with 50%  $\text{H}_3\text{PO}_4$  for 5 seconds and 3%  $\text{NaOCl}$  for 10 minutes, with subsequent dehydration protocol in ascending ethanol series (50, 70, 80, 90, and 3 $\times$ 100%), fixation in hexamethyldisilane (HDMS), gold /palladium sputtered, and examination on backscattering electron mode at 10 kV (Phenom ProX, Phenom-World). A skilful blinded evaluator inspected all the elongations of the bonded interfaces of each disc, and illustrative electron micrographs with 2.500 $\times$  magnification was taken.

### 4.2.3.2 SEM Detection of Crack Propagation Sites (Study III)

Specimens (n=10/group) that endured a minimum of  $1 \times 10^4$  loading cycles were examined applying scanning electron microscopy (SEM) to differentiate the superficial morphology and detect the failure of origin. All specimens were carefully wet-polished with SiC papers with 600-, 1200-, 2000-, and 4000-grit (Carbimet &

Microcut, Buehler Ltd) under 30 seconds each. The specimens received an ultrasonic bath in distilled water for 60 seconds, with following ascending dehydration series of ethanol solutions, finalized with 100% ethanol. A finalizing chemical dehydrating process applying hexamethyldisilane (HMDS) was done overnight. While formalin fixation expressively disturbs the enzymatic activity inside the tissue, substituting fixatives were applied in this study for preservation of tissue morphology and enzyme activity equally. Afterwards, specimens were gold/palladium sputter-coated and examined at 10 kV (Phenom ProX, Phenom World). SEM micrographs using  $3.000 \times$  magnification, were taken from all segments on the tensile side of the beams covering the entire extension.

#### 4.2.3.3 Statistical Evaluation (Studies I-III)

For smear layer removal, the means value and standard deviation range of the smear layer scores, and the median were recorded and depicted for all groups. The normality test was accomplished by the Tukey HSD test in each group. Statistical significance was set at  $\alpha = 0.05$ . A one-way analysis of variance (ANOVA) was used to assess normality test for comparison of the three diverse groups. If the normality was defied, then the Kruskal–Wallis Test was to be used as an option (Study I).

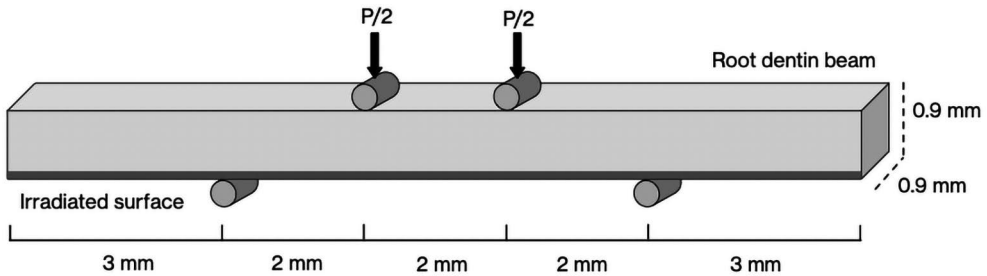
Because push-out data was typically dispersed (Kolmogorov-Smirnov test  $p=0.182$  and homoscedastic Levene's test  $p=0.883$ ), two-way ANOVA complemented by the Tukey's tests was employed to evaluate bond strength values. A significance level ( $\alpha$ ) was set at 0.05. For evaluation, IBM SPSS Statistics for Windows, version 26 (IBM, Armonk, NY, USA) was implemented (Study II).

The Shapiro–Wilk and Brown–Forsythe tests were applied to measure normality and homogeneity of variance in the 4-point flexural strength and cross-sectional datasets. Flexural strength values were obtained from quasi-static loading tests, and differences in cross-sectional area were evaluated using a one-way analysis of variance (ANOVA). Fatigue life distribution data were evaluated using the Kruskal–Wallis one-way analysis of variance on ranks. The level of significance was set at 5% ( $\alpha = 0.05$ ). All statistical analyses were completed using SigmaPlot for Windows (version 15) (Study III).

#### 4.2.3.4 Mechanical Evaluation of Laser-treated Dentin (*Study III*)

A universal testing system (ElectroPlus 1100 Instron, UK) with a load capacity of 250 N and sensitivity of 0.025% was used to conduct quasi-static and cyclic four-point flexural tests on root dentin samples. The design for the jig, sample arrangement, and loading configuration are illustrated schematically in **Figure 7**. Quasi-static loading was applied at a displacement rate of 0.05 mm/min. The flexural

strength (FS) of the beams was calculated using standard beam theory. FS was obtained from the maximum recorded load ( $P$ , N) and the beam dimensions—width ( $b$ ) and thickness ( $h$ ), both in mm—according to the following equation:  $FS = 3Pl/bh^2$ , where “ $l$ ” is the distance between the interior and exterior supports ( $l = 2$  mm). Each group comprised twelve specimens ( $n = 12$ ). All specimens were tested using the same flexural configuration and subjected to load-controlled cyclic loading at 4 Hz with a stress ratio of 0.1 ( $R = \text{minimum load} / \text{maximum load}$ ).



**Figure 7.** Schematic diagram illustrating the arrangement of specimens and the loading configurations. These configurations were used to record both the 4-point-flexure under quasi-static loads, and the stress-life fatigue behaviour at 4 Hz under cyclic loads.

The cyclic loading protocol respected a staircase fatigue approach. Testing began at approximately 95% of the flexural strength determined from quasi-static loading, followed by sequential 10% declines in load until failure occurred. The procedure was carried out until a flexural stress amplitude (MPa) was identified at which the specimens survived  $1 \times 10^6$  cycles without fracture. The cyclic stress amplitude was then plotted against the number of cycles to failure on a logarithmic scale. The amplitude for cyclic stress was plotted in terms of the number of cycles to failure in log-base format. The obtained data were fitted using a nonlinear regression based on a Basquin-type model, described by the equation  $\sigma = A N^B$ , where  $A$  and  $B$  represent the fatigue strength coefficient and the fatigue strength exponent, respectively.

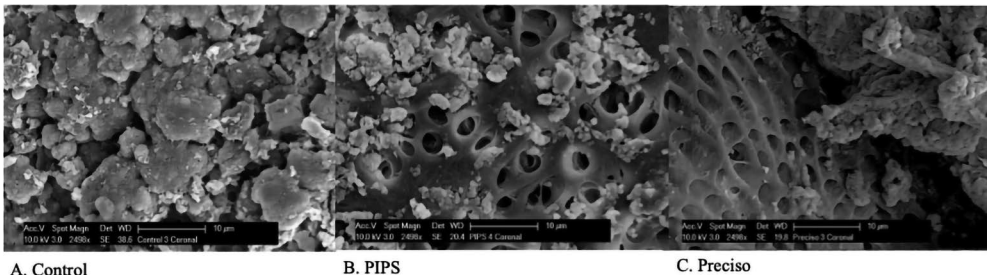
The evident endurance limit was assessed from the models for a fatigue limit outlined at  $1 \times 10^7$  cycles. For each group, twenty-five specimens were evaluated.

# 5 Results

## 5.1 The Removal of Smear Layer (Study I)

The control group presented a constant smear layer concealing the canal walls throughout sections. On the contrary, the other two groups revealed a slighter volume of dentinal debris in the coronal third of the root canal, with debris forming a thinner layer along the canal walls. Specimens from the PIPS and the Preciso groups appeared to have a reduced volume of residues in the middle part of the root canal related to the control group. In the apical part, however, the cleaning effect was deficient in nearly all specimens.

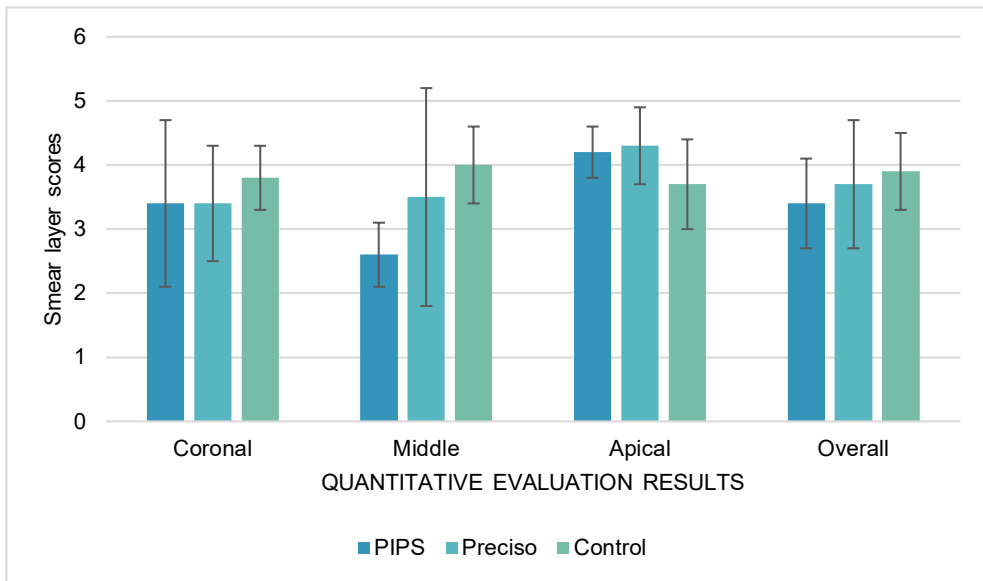
In the coronal part of the root canal, the PIPS group recorded significantly improved scores compared to the Preciso group ( $p < 0.05$ , Tukey HSD test), **Figure 8**. In the middle section, the PIPS group was significantly different with smaller score from the Preciso, and Control groups with the smallest score ( $p < 0.05$ , Tukey HSD test). In the apical third, Preciso scored higher compared to the PIPS group.



**Figure 8.** Representative SEM images showing smear layer. **A.** Control group in the coronal presents a third thick smear layer covering the internal wall of the root canal. In the other two groups the coronal third showed reduced amount of dentin chips and pulp remnants layering the canal surface after one laser treatment. **B.** PIPS group (Er:YAG). **C.** Preciso group (Er:YAG).

In the PIPS group, the decrease in smear layer score was extremely dissimilar from the coronal to the middle part ( $p < 0.05$ , Tukey HSD test). In Preciso group the cleaning efficacy weakened from the coronal to the apical part of the canal. Also, in the Preciso group, the scores exhibiting the coronal and middle section exposed a substantial alteration related to the control group. A significantly higher score was

observed in the apical section ( $p < 0.05$ , Tukey HSD test). In the control group SEM evaluation demonstrated that conventional root canal treatment using only NaCl as the irrigant, is not successful in eliminating the smear layer. In nearly all segments of the root canal, the surface was concealed by a thick layer of debris, and tubules could not be detected. Statistically significant differences were identified. Quantitative analysis of smear layer eradication is shown in **Figure 9**.

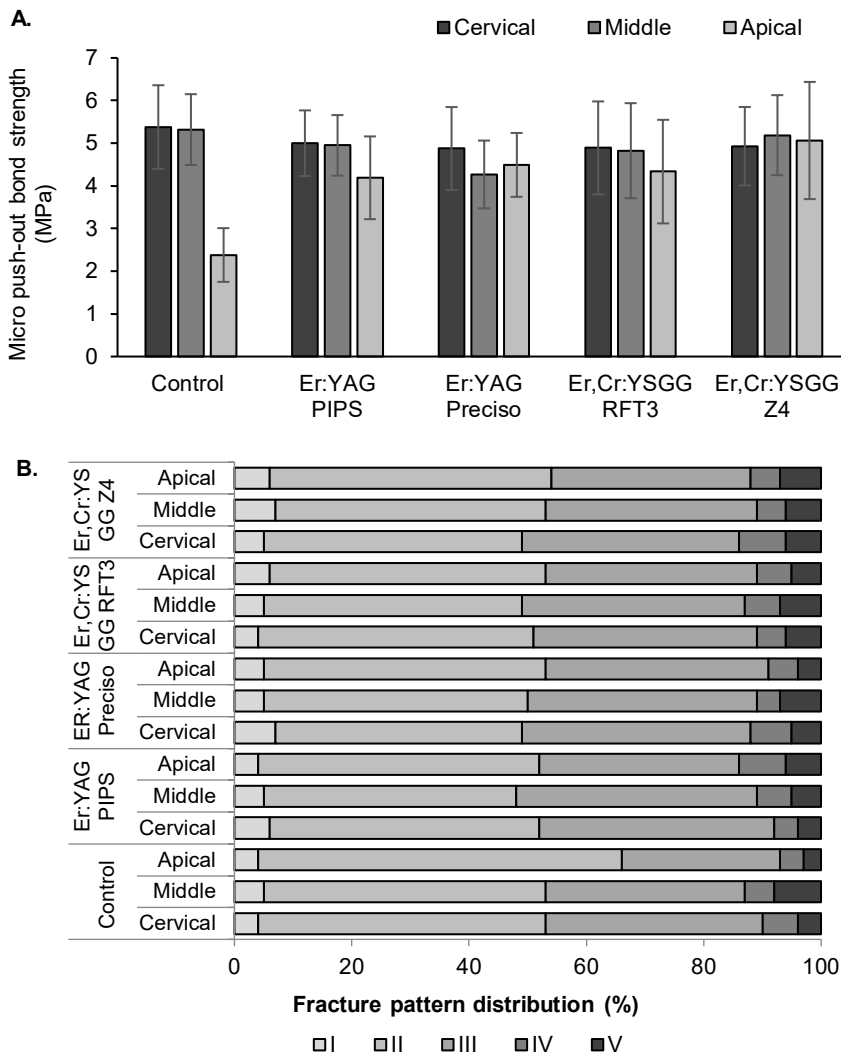


**Figure 9.** Quantitative analyses for smear layer scores. Mean value and Standard Deviation for each group. Mostly, the Preciso group delivered superior score related to PIPs group ( $p < 0.05$ ) scores (x indicates scores 0–5, y different groups and segments) (from Study I).

## 5.2 Intraradicular Bond Strength and Fracture Patterns (Study II)

Two-way ANOVA revealed that the “root section” ( $p < 0.0001$ ;  $\eta^2 = 0.211$ ) and the interaction “laser irradiation protocol\* root section” ( $p < 0.0001$ ;  $\eta^2 = 0.267$ ) had significant effect on micropush-out bond strengths. **Figure 10** summarizes micropush-out bond strengths. The control group (non-irradiated) exhibited no substantial alterations among the cervical and middle thirds of the root ( $p > 0.05$ ). The apical third of control specimens showed meaningfully minor bond strengths, around –56%, compared to cervical and middle thirds ( $p < 0.05$ ). No meaningful alterations were observed regarding to irradiation protocols/ tips mirroring cervical and middle thirds ( $p > 0.05$ ). The effect of laser irradiation on cervical and middle thirds was not meaningfully dissimilar compared to the correlated control root sections ( $p > 0.05$ ). Laser irradiation created significantly higher bond strengths on the apical root section (from 50% to 2.1-

fold) related to the control apical section ( $p < 0.05$ ). Fracture patterns could mainly be characterised by adhesive failures regarding resin cement and intraradicular dentin (type II) followed by mixed failure of resin cement layering part of the post surface (type III). A greater incidence of adhesive failures was exhibited among control samples in apical root segments compared to those of the remaining groups.



**Figure 10.** (A) Micropush-out bond strength (MPa) means, and standard deviations ( $n=8$ ) of fibre posts luted with self-adhesive resin cement (U200, 3M Oral Care). Intraradicular dentin was exposed to irradiation with diverse lasers applying diverse tips. Different uppercase letters indicate significant alterations in between root segments using the equal laser irradiation protocol. Different lowercase letters indicate significant alterations in among corresponding root segments with diverse laser irradiation protocols. (B) Fracture patterns (%) for all groups (from Study II).

### 5.3 Nano Leakage (Study II)

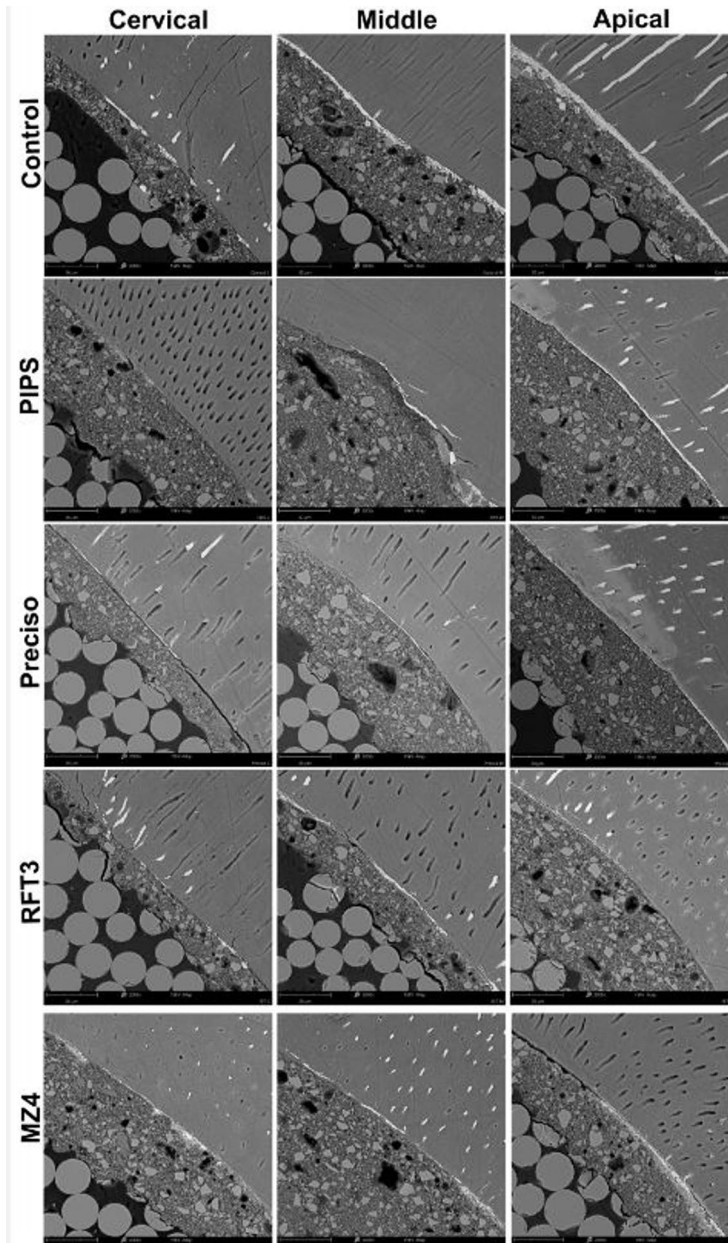
Representative SEM micrographs of silver uptake for each sample group are presented in **Figure 11**. All specimens exposed nano leakage, demonstrating porous-liquid-filled zones lengthways bonded interfaces. The prolongations of silver deposits deviated, rendering to the root segment and laser irradiation protocol. Overall, nano leakage occurrence amplified with root depth along apical>middle>coronal thirds. Laser irradiation applying the examined tips condensed nano leakage levels correlated to control (non-irradiated) specimens for all root segments. Diminished levels were furthermore obvious in apical root segments, which seemed lesser silver deposits related to apical control samples. Preciso, RFT3, and MZ4 laser tips could show uniform extension of silver uptake at the cervical and middle root parts, correspondingly.

Cervical root segments with PIPS irradiation seemed smaller in nano leakage appearance. Nevertheless, silver deposits with PIPS seemed larger at middle root segments related to Preciso, RFT3, and MZ4. Nano leakage levels at the apical root parts were described as PIPS>MZ4>Preciso>RFT3.

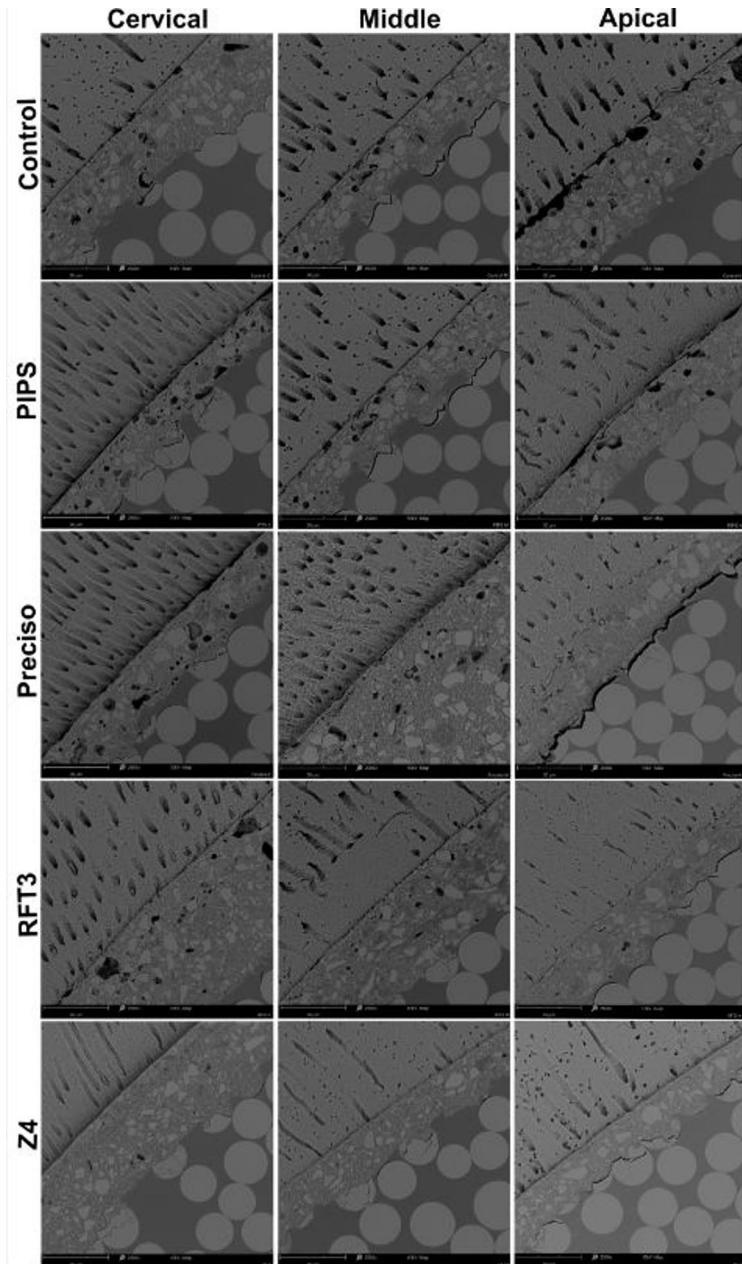
Nano leakage characters for the control group were mainly reticular silver deposits engaging the cement-dentin interface with extensions over the cement layer, with cumulative complete thickness at deeper intraradicular depths. Specimens exposed to laser-irradiation exhibited principally slimmer reticular silver deposits with a lesser annex over the cement layer.

### 5.4 SEM Interfacial Characterization (Study II)

Demonstrative SEM micrographs of fibre posts luted to intraradicular dentin for each sample group are presented in **Figure 12**. The self-adhesive cement exposed a shallow interaction with dentin. Defects and irregularities like apertures at the cement-dentin interface were frequently documented for all bonding protocols unrelatedly of intraradicular penetration. A distinct cement–dentin interdiffusion area was not detectable at magnifications up to 20.000×, independent of the application of laser irradiation. While the incidence of interfacial defects enlarged with intraradicular depth in control samples, laser irradiation was able to reduce cement-dentin gap development in deeper intraradicular zones. Irregular resin-tag development was recognised in all root sections with the use of RFT3 and in the coronal root section when MZ4 was used. In the other groups, involving the control group, tag formation was hardly recognised in restricted zones without a resilient distribution outline. Root segments in middle and apical segments after irradiation with Preciso, lightly exhibited an acid-resistant layer of 0.8–1.3 µm thickness, which was detected in few specimens not having a consistent dispersal lengthwise the cement-dentin border.



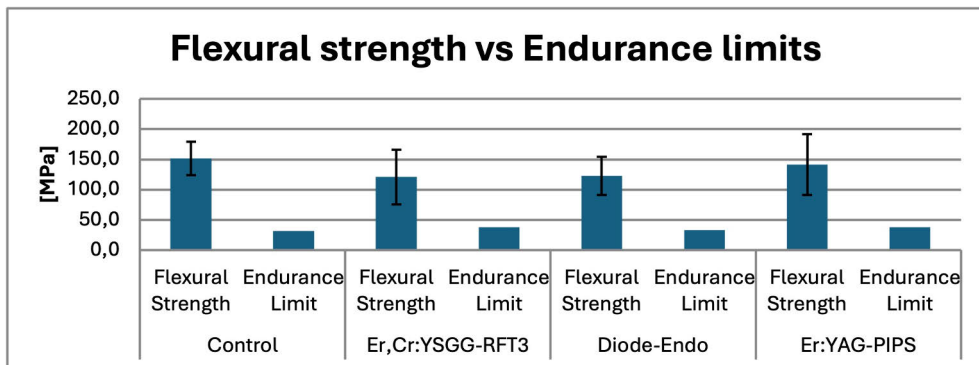
**Figure 11.** Representative SEM micrographs illustrating immediate nano leakage at the interface between fibre posts bonded to intraradicular dentin with self-adhesive resin cement following laser irradiation using different fibre tips (Study II).



**Figure 12.** Representative SEM micrographs of fibre posts bonded to laser-irradiated intraradicular dentin using self-adhesive resin cement and different fibre tips (Study II).

## 5.5 Quasi-static 4-point Flexural Strength (Study III)

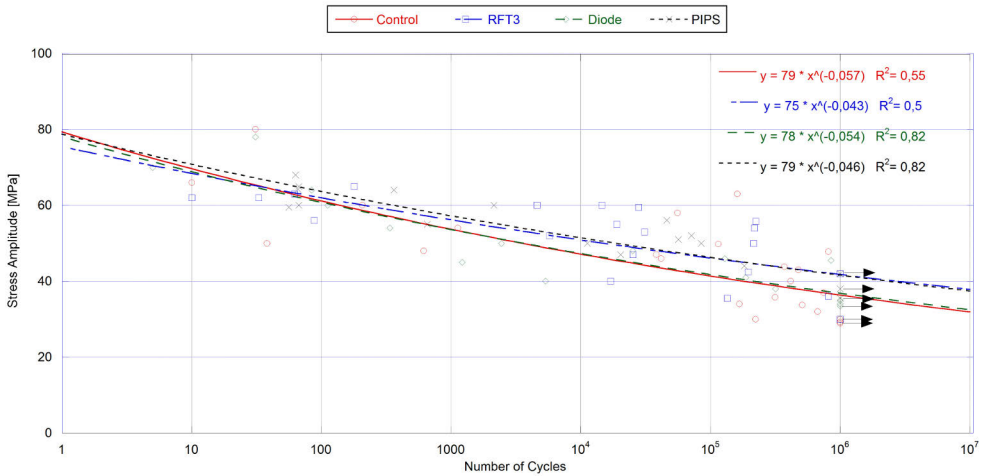
Strength results under quasi-static loading are accessible in **Figure 13**. Flexural strength values varied between 121 MPa and 151 MPa in Er,Cr:YSGG, and control groups, correspondingly. One-way ANOVA exposed that none of the used laser protocols produced a substantial alteration ( $p>0.05$ ) in the 4-point flexural strength of the tested beams. The results were paralleled with the strength of the laser-treated and untreated beam samples. Root dentin specimens exhibited no significant differences concerning to sample size in among groups ( $p>0.05$ ).



**Figure 13.** Flexural strength, stress-life fatigue response, power law constants and estimated endurance limits for control and experimental groups (from Study III).

## 5.6 Fatigue Behaviour and Endurance Limits (Study III)

Fatigue life diagrams (S-N curves) are revealed in **Figure 14**. Regression analyses with basquin-type power law models are registered for all groups to depict the mean fatigue strength distribution. Kruskal-Wallis One-way analysis of variance on Ranks test exposed no significant differences in stress amplitude among tested groups ( $p>0.05$ ). Nevertheless, the highest fatigue strength ensued for groups irradiated with Er:YAG and Er,Cr:YSGG. Diode and control groups produced slighter fatigue strengths. The stress-life fatigue constants for all groups were recorded and applied to appraise the evident endurance limit for every group at  $1 \times 10^7$  cycles. The highest apparent endurance limits similarly occurred with both erbium laser protocols. Er:YAG (PIPS) and Er,Cr:YSGG (RFT) endurance limits were 18% and 19% higher than those of the control group.

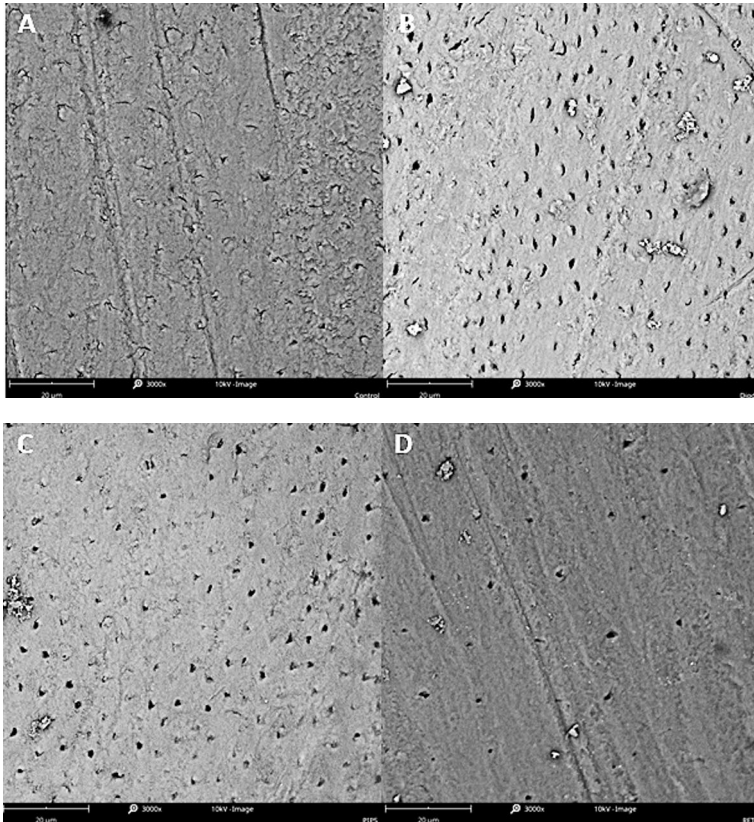


**Figure 14.** Stress-life diagrams for root dentin specimens after laser-assisted treatments. Notice, that data points with arrows signify samples that reached  $1 \times 10^6$  cycles, and the test was consequently finished. The  $R^2$  values signify the coefficient of determination (from Study III).

The figure shows both the number of cycles to failure for specimens that fractured and the maximum number of cycles that did not fail (run-out, indicated by arrows). Therefore, the cycle number is represented in the graph, while the arrows indicate specimens that reached the predefined test limit without failure.

## 5.7 Dentin Surface After Laser-assisted Treatments Scanning Electron Microscopy (SEM) (Study III)

SEM images could reveal morphological variations among groups. The control group demonstrated a thick smear layer with only rare detectable dentinal tubules. The diode laser group displayed partly visible tubules with few smear layer. On the contrary, the Er:YAG and Er,Cr:YSGG groups exhibited great smear layer amount covering tubule openings leaving only a slight portion visible **Figure 15**.



**Figure 15.** Representative SEM images illustrate surface morphological alterations among the groups. **(A)** The control group exhibited a dense smear layer with limited amount open dentinal tubules. **(B)** The diode laser group showed partially exposed tubules with reduced smear layer presence. On the contrary, **(C)** the Er:YAG group and **(D)** the Er,Cr:YSGG group demonstrated greater smear layer covering the surface, with only limited tubule openings observed (from Study III).

## 6 Discussion

### 6.1 Photo-acoustic Cleaning

This study series aimed to evaluate two different fiber tips combined with different activation protocols in laser-assisted endodontic procedures *in vitro*, in order to identify a safe and effective protocol for deep cleaning under *in vivo* conditions—*specifically focusing on approaches that do not rely on chemical agents*. Many former studies have also shown the difficulty with irradiation without causing structural changes while trying to eliminate the remaining smear layer (Huang et al., 2023; Blakimé et al., 2023; Oliveira-Tavares et al., 2023). Anatomical alterations or other damage inside the root canal are often consequences of irradiation in dry canals, usually with Nd:YAG or diode, generally caused by thermal outcome.

Mechanical instrumentation leaves 35–53% of the root canal structure unaffected (Peters et al., 2001). Even in the current study (Study I), this could be approved by the outcomes valuated in the control group (group 3), with traditional treatment, without laser irradiation. Even though methods, instruments, and the amount of intracanal remedies have developed, endodontic therapy can nevertheless be unsuccessful. Researchers have attributed such failures to the incomplete microbial decontamination from the root canal structure and tenacious infection. *Enterococcus faecalis* is the dominant infectious genus in root canals with endodontic failure. It is reported in 64–78% of persistent or secondary infection cases (Chiniforush et al., 2015). Several treatment technologies have been presented in the endodontic field, targeting excellent decontamination of the root canals before obturation. Among these newly introduced treatment modalities, dental lasers may deliver a superior approachability to unapproachable portions of the tubular network because of their improved ability to penetrate inside dentinal structures (de Souza et al., 2008). The SEM images from the first study showed that when Er:YAG was utilized with the conical-ended, radial-firing PIPS tip, and the more traditional bare fibre tip Preciso, both succeeded better in the coronal section and in the middle section of the root canal system. Still, when using the 0,9% saline solution as the only irrigant, neither of the tip models could properly enhance the cleaning of the apical part (Sippus et al., 2018). However, the findings were obtained under the specific conditions of the

current study and do not rely with other studies, when irrigants as EDTA and NaOCl were used (Meire & De Moor, 2024).

Moreover, the effect of lasers on microbial surfaces, as imagined by atomic force microscopy, exposed severe variations, which are noted as transformations in the morphology of bacterial cell surfaces, together with compound cell lysis signs. In a former study, a dry mode laser irradiation Er,Cr:YSGG group led to a microbial decrease of proximate 82.5% at 0.75 W, which is equivalent to the 77% microbial decrease in an experiment utilizing Er,Cr:YSGG irradiation done by Wang et al., 2007, at 1 W, when tested with paper points. This insignificant difference in the microbial decrease may be accredited to the variance in the laser irradiation time, which was 2 minutes in the latter study (EL-Gendy et al., 2017), while it was only 40 seconds in the first study (Wang et al., 2007), as former studies have stated a decrease in the microbial count when the power and duration of laser irradiation increased (Gordon et al., 2007; EL-Gendy et al., 2017).

Nd:YAG and diode lasers remain widely used in endodontic treatments. The key challenge is generating enough heat to effectively eliminate bacteria while avoiding damage to the surrounding periodontal tissue. Consequently, researchers have explored strategies to minimize temperature rise during laser-assisted procedures. The thermal outcome could be diminished when utilizing low energy with short pulse durations ending in high peak power (Blanken et al., 2009; DiVito et al., 2011, 2012). Since erbium laser energy is absorbed almost entirely near the fiber tip, vaporization occurs before any significant heating of the irrigation solution. The second factor, peak power, does not affect temperature directly but enhances fluid agitation. Besides thermal alterations, the influence of ablation on dentinal surfaces might be minor when utilizing parameters to a lesser extent. The Er:YAG laser ablation threshold is declared to exist in the range of 1 to 4 J/cm<sup>2</sup> (Lin et al., 2010; DiVito et al., 2011). In study I, the PIPS tip of *600 mm diameter* was used with an energy setting of 20 mJ, corresponding to 4 J/cm<sup>2</sup>. It is worth noting that the currently used pulse energy remains significantly lower compared to settings in former studies, with the consequence that thermal damage can be inhibited. The applied 50  $\mu$ s pulse duration is responsible for a peak power of 400 W. According to a previous study, the new conical and stripped laser tips with excessive lateral emission were used compared to older bare tips with more forward emission (George & Walsh, 2010). The study could specify that conical tips can be used safely. The importance of water irrigation with radial firing tips was even documented to reduce thermal alterations during laser irradiation (George & Walsh, 2010). In this current study series, all the irradiation times used were adopted from manufacturers' recommendations, depending on the laser wavelength and tips used.

Dental lasers, by producing shock waves, can present a crucial function in eliminating dentinal residuals after instrumentation during endodontic treatment.

Equally, the diverse remnants can be eradicated when activating the irrigant solution in the root canal system applying a Preciso tip with an Er:YAG laser. During the irradiation pulse, the principal vapor bubble swells till it collapses. The breakdown produces pressure waves with supersonic speed (shock waves) and waves with sonic speed (acoustic waves) within the irrigant liquid (Jezeršek et al., 2020). After the principal vapor bubble collapses, the secondary minor cavitation bubbles are formed due to the quick and extensive changes within the irrigant liquid. These extreme intracanal pressure waves generate cavitation laterally and lengthwise in the root canals, leading to excellent cleaning results. In the current study, the PIPS fibre was placed only in the coronal part near canal openings with no contact to cavity walls and held steady under irradiation. In conventional treatment, an up-and-down motion is mandatory in the irrigant since the entire root canal area must be exposed to laser irradiation. Spiral motion was used when testing the Preciso tip model. Under the conditions of the present investigation, a dual effect occurred because the laser beam not only activated the irrigant but also directly irradiated the canal wall. The irradiation was done with *irrigant (NaCl)* but not continuously flowing like when PIPS was used. Therefore, creating ledges with Preciso is riskier than with PIPS. Still, the risk of irrigant extrusion has been shown apically following the laser activation at the present power settings when the long endodontic fibre tips are used inside the root canal. A previous study showed that dye penetration through the apical foramen was twofold when the laser fibre was positioned at 4 mm in comparison to 5 mm. (George & Walsh, 2008). Consequently, the current judgment used a range of 5 mm from the apex to the positioning of the laser fibre. Also, if the laser tip is inserted just in the orifices of canals, it could be overly distant for the irrigant stream to be activated in the remote portions of the root canal. There is academic debate if the remoteness might affect the bactericidal efficiency in the apical area. However, two confocal laser scanning microscopy studies have demonstrated deep penetration of the irrigant into the dentinal tubules of the apical root canal dentine (Azim et al., 2016, Akdere et al., 2023).

The original solution Dakin used was an aqueous solution of 0.5% NaOCl (Dakin, 1915). NaOCl solutions with higher concentrations were later recommended for endodontic debridement (Grossman & Benjamin, 1967). The antiseptic effectiveness of sodium hypochlorite solutions is distinctly related on the concentration (Radcliffe et al., 2004), tissue dissolving ability (Zehnder et al., 2003), and even the acid potential. Severe cases have been documented when concentrated NaOCl solutions were unintentionally forced into surrounding periodontal tissues or with direct skin contact when the solution was carelessly applied. Idealistically, increasing hypochlorite concentrations over 1% NaOCl in irrigation liquids for a better outcome might not be a wise option (Abou-Rass & Oglesby, 1981). Therefore, one complementary method to improve the efficacy of hypochlorite irrigants in

endodontic treatment could be laser-assisted root canal therapy for their tissue-dissolving ability (DiVito et al., 2012).

The Er,Cr:YSGG tip Z4 was used in the Study II, parallel to the Er:YAG Preciso tip, both bare end fibres, in comparison to radial firing tips PIPS (Er:YAG) and RFT3 (Er,Cr:YSGG). Despite that, the Er:YAG laser, with the wavelength of 2.94  $\mu\text{m}$ , is highly absorbed in water, and when activated in a small volume of irrigant liquid, operating in short pulse duration ( $<150 \mu\text{s}$ ), gaining high peak power, could end in a shock wave (photomechanical phenomenon), which can kill micro-organisms and eliminate the smear layer from the root canal structure. Though, the result of this study presents that an outcome like this occurred just in the tooth's upper and medial section during endodontic treatment. The purifying effect was decreasing from the coronal part to the apical part. The compelling point is that in former studies (DiVito et al., 2012), when Er:YAG laser irradiation was united with EDTA irrigation, eliminating the smear layer was more satisfactory than with a non-chelating NaCl solution. Therefore, the PIPS method with EDTA irrigant can be a reasonable pattern for eliminating the apical smear layer for ultimate results. The outcome of pulsed Er:YAG in eliminating microbes is non-thermal, rejecting the uninvited outcomes of temperature rise. When the Preciso tip grants a modest technique to the apical part, PIPS could be merely applicable when utilized in curved, thin canals where the structural root canal anatomy limits supplementary methods.

## 6.2 Bond Strength After Laser Treatment (Study II)

The rationale for selecting a self-adhesive resin cement for the current study (Study II) was the increasing clinical use for intraradicular bonding among clinicians. Beyond their ease of use, self-adhesive resin cements are less sensitive to intraradicular moisture conditions. (Aleisa et al., 2013; Maroulakos et al., 2018), generate lesser polymerization stresses (Oliveira et al., 2011; Bergoli et al., 2012; da Costa Ribeiro et al., 2024; Brum et al., 2025), and thus could generate higher push-out bond strengths compared to supplementary types of self-adhesive resin cements (i.e., etch-and-rinse and self-etch) (Sarkis-Onofre et al., 2014; Maroulakos et al., 2018). As laser irradiation applying end-firing or radial-firing tips increased push-out bond strengths to apical root parts, the first null hypothesis was rejected.

Despite the category of resin cement, major studies present lower bond strengths at apical root portions (Sarkis-Onofre et al., 2014; Maroulakos et al., 2018; Pelozo et al., 2019), which could be confirmed by the current study. The morphological structure of apical root dentin is much dissimilar from cervical and middle root portions, which makes bonding complicated (Mjör et al., 2001; Ekambaram et al., 2015; Maroulakos et al., 2018; Özcan & Volpato, 2020). Other than disadvantageous dentin morphology (Mjör et al., 2001; Violich & Chandler, 2010; Ekambaram et al.,

2015; Maroulakos et al., 2018; Özcan & Volpato, 2020) many points contributed to reductions in bond strength at profounder radicular portions, like efforts in succeeding intraradicular purifying, reduced polymerization of resin-based adhesives (Ekambaram et al., 2015; Özcan & Volpato, 2020), and elevated flaw distribution (da Silva et al., 2019).

Effective intraradicular bonding depends on deep penetration of adhesives into dentinal tubules, forming resin tags and a hybrid layer that improve micromechanical retention and sealing. The process is not possible with NaCl. This penetration is achieved primarily through smear layer removal with 17% EDTA, which opens dentinal tubules after instrumentation. Sodium hypochlorite (NaOCl) dissolves organic tissue and collagen but cannot remove the inorganic component of the smear layer alone. Therefore, when used together with EDTA, both organic and inorganic debris are removed, maximizing tubule openness and enhancing adhesive penetration. Comparing the hybrid layer (dentin-resin interface) and deep tubular penetration (sealer tags) highlights distinct aspects of endodontic sealing and bonding. While the hybrid layer is essential for coronal restoration and dentin sealing, laser activation—especially laser-activated irrigation (LAI)—is more effective in promoting deep sealer penetration into dentinal tubules. Studies have demonstrated that laser activation using Er,Cr:YSGG lasers achieves significantly greater sealer penetration depths than conventional techniques (Kaplan et al., 2023). Laser treatment in current study could enhance intraradicular bonding. Multiple tries have been formerly suggested to eradicate this bonding issue to permit enhanced resin cement-dentin interactions, although these studies were all conducted using NaOCl and EDTA (Kimura et al., 2000; Altundasar et al., 2006; Violich & Chandler, 2010; Ekambaram et al., 2015; Özcan & Volpato, 2020). EDTA is widely applied as a chelating agent for eradicating the smear layer in root canal treatments. Nevertheless, bare EDTA irrigation might not be appropriate to enhance the push-out bond strength of the presently assessed self-adhesive cement (Jitumori et al., 2019). There is an observable effect even at low concentrations when using LAI with NaOCl, as LAI increases the reactivity of NaOCl (Macedo et al., 2010; Betancourt et al., 2020). Additionally, the laser itself still contributes to smear layer removal. The current study did not apply canal irrigation solutions that could eliminate the smear layer. This study series aimed to separate the result of laser treatment on push-out bond strengths. Hence, a 0.9% NaCl solution was the only irrigant applied under laser treatments.

The nonsurgical laser-assisted endodontic treatment has been evident from the early 1970s. The Er:YAG (2.940 nm) and Er,Cr:YSGG (2.790 nm) were specifically chosen because of their high absorption in water-based irrigating liquids having a very good superficial debriding effect (DiVito et al., 2012; Walsh, 2003). The tested middle infrared lasers (Altundasar et al., 2006; Arnabat et al., 2010; DiVito et al.,

2012; Kimura et al., 2000; Mir et al., 2009) with their debriding action, promoted to slightly over double push-out bond strengths in apical area by enhancing the resin interaction between cement-dentin. This consequence could be detected solely at the apical root portions, indifferent to the used fibre tips. The apical section of root canals is commonly more challenging to get purified because of the continual tapering of the root canals while approaching the apical part. When tested in dry canals, the universally used dental lasers allowed excellent approachability to apical portions due to their higher penetration depth inside dentinal structures (Schoop et al., 2009).

The findings of a later study suggest that the use of *Er,Cr:YSGG laser irradiation alone* is significantly less effective in removing the smear layer compared with the *conventional gold-standard irrigation protocol of 2.5% NaOCl followed by 17% EDTA*, particularly in the apical third of the root canal walls. Furthermore, severe erosive changes were observed along the root canal walls in specimens treated with Er,Cr:YSGG laser irradiation. Despite these observations, laser irradiation resulted in only minimal loss of mineral content from the root canal dentin when compared with EDTA irrigation, with no statistically significant differences detected in the Ca/P ratios between the groups (Alhadi 2016).

All used tips also enhanced the unity of resin cement-dentin interfaces; thus, the second null hypothesis was rejected. Diverging from the push-out results, the formation of the tips influenced the interfacial bonding quality. The debriding effect decreased the nano leakage levels. Former studies could confirm that roots that were not pretreated on dentinal surface (control group) stated weaker outcomes in bonding (Pelozo et al., 2019). Er:YAG and Er,Cr:YSGG lasers could be pondered a novel alternative to conventional root canal therapy with satisfactory debriding effect (DiVito et al., 2012; Guidotti et al., 2014; Josic et al. 2022; Brum et al., 2025). This finding states the outcome of laser-assisted endodontic procedures to enhance intraradicular resin cement-dentin interface and create less-porous interfaces. The tested fibre tips (end-firing and radial-firing) present diverging deliveries of laser energy. PIPS was intended to be positioned basically inside the pulp cavity. PIPS's photoacoustic shock waves consistently lessen over the remoteness when approaching the apical portion (Jiang et al., 2016). This range indicates further nano leakage decrease in cervical root portions. Differing from the other tips, the difficulty to achieve the apical part, restricted the laser irradiation of profounder root portions, causing advanced silver deposits. The configuration of laser beam emission even has an impact on intraradicular nano leakage. The RFT3 delivered the lowest nano leakage levels at the apical portion. Because of more consistent irradiation outcome on the root canal walls, silver uptake was reduced. Radial-firing tips show a conical configuration where the irradiation is widened forming an extensive cone, causing enhanced opening of dentinal tubules. The spherical emission has a positive influence on eliminating debris and smear layer, as formerly reported, and can

decrease nano leakage levels more efficiently compared to the bare-ended Preciso (Er:YAG) and MZ4 (Er,Cr:YSGG) tips. Correspondingly, the largest diminishing in silver uptake was detected merely near the apical portion. The vicinity of the fibre tips to canal walls at the narrow apical part can improve the prospective deep-cleaning effect, therefore diminishing nano leakage to broader extents than in other root portions. Blanken et al. were the earliest researchers to state the effect of LAI and to demonstrate the impact of photoacoustic cleaning. They were able to verify liquid movements as high as 20 m/s (72 km/h) when applying Er,Cr:YSGG laser with MZ4 Endotip by Biolase. The rapid irrigant movements were credited to cavitation resulting from vapor bubbles increase and collapse forces (Blanken et al., 2009).

Microscopic evaluation of the cement-intraradicular dentin interfaces reveals that the tested laser tips and protocols were equally sufficient in improving mechanical interaction. The enhancement stayed noticeable when monitoring the irradiated and non-irradiated specimens, particularly at the apical portions. As expected, the bonded interface exhibited flaws, reflecting the high-stress intensity as an outcome of a tall C-factor inside root canals. Challenges in eradicating the smear layer from the apical portions caused many flaws (Huang et al., 2023a; Blakimé et al., 2023; Oliveira-Tavares et al., 2023). In the current study, superficial etching was applied to the bonded interfaces prior to drying and sputtering, following preparation protocol for the SEM. The generally applied preparation procedure with SEM for resin-dentin interfaces disperses the remaining observable smear layer as hollow spots at the interface. Separation if these empty spaces initiated from polymerization stresses or barely from eradicating the smear layer, falls out of the scope of this study. However, the diminished rate of occurrence of defects and apertures on laser exposed specimens demonstrates that diminished interfacial defects could be linked with laser-generated debris eradication before bonding (Schoop et al., 2009). The extension wherein cement-dentin interfaces were enhanced was altered consistent with tip choice. Fibre tips having distinct energy distributions altered the laser's capability to extend to all canal areas. The radial-firing tip RFT3 delivered the utmost efficient interactions between cement-dentin. The more expansive irradiation zone with lateral spreading from the tip enhanced laser irradiation towards root canal walls. The outcome with bare-ended tips is different, as laser distribution is mainly oriented towards apical portion. Minor resin tags could be detected in cervical part for intra-canal and bare-ended tips (i.e., Preciso, MZ4), whereas numerous tags were revealed in every part of the root canal, while utilizing RFT3. This demonstrates excellent cement-dentin interaction and extra coherent integration between resin-cement to the root canal walls. Subsequently, radial-firing tips were superior to conventional tip prototypes in increasing resin-cement bond to intraradicular dentin

merely at the distant apical parts. Supplementary studies are obligatory to confirm the benefits of new improved fibre tips in supplementary laser protocols.

When fibre-reinforced composite (FRC) posts are applied, the fracture resistance and patterns increase (Salameh et al., 2008). Moreover, the remaining coronal tooth construction also appeared to impact the outcomes. Although fracture strength experiments in laboratory environment cannot imitate intra-oral loading circumstances, they can compromise precise settings to prepare and test the samples, consequently enabling a comparable assessment of the variables during the study (Kelly, JR 1999).

Respective studies had assessed the fracture strength of teeth after root canal treatment, but straight evaluation amongst these studies is highly problematic because of multiple variables like the tooth structure, preparative and restorative techniques, material variances, loading method, and most prominently, the classification of the point of failure (Pontius & Hutter, 2002). Uninterrupted loading of the samples until devastating failure will end in baseless excessive fracture loads as destruction was previously presented to the samples at considerably minor loads. A minor clinical impact can be put on the restoration loading to complete failure since the destruction has already happened. Additionally, it is appropriate to reach the total failure point when core materials are tested if these are intended to be applied in extensive restorations. Even after the primary loss of structure, with the possible incidence of cone fractures, the restoration can bear more loading (Aboushelib et al., 2007).

Seeing the primary failure, the hasty fall of load, the failure load can be considered clinically significant, since starting from this, the injury will spread due to fatigue (Aboushelib et al., 2007). Suppose a flat tooth structure maintains the core structure. In that case, no lateral forces can be developed, which fractures the tooth and causes deformation in all surfaces, distributing bare condensed load, harming the tooth structures. Identical outcomes could be attained one year after (Salameh et al., 2008).

According to the existing data, the FRC post-placement directly affected the fracture strength of the restorations related to controls (Hatta et al., 2011; Shah et al., 2021). The posts were able to transmit the loading stress partially towards the primed root canals, thereby delivering the load throughout a larger area zone of the tooth structure and potentially improving stress distribution. Posts adhesively bonded to the dentinal structure allow effective transmission of the applied load (Sorrentino et al., 2007). The width of the FRC post plays a meaningful role in delivering the stress forces. Therefore, the required size for the root canal preparation must be pondered with the following expected mechanical stresses (Lassila et al., 2004). The effect of the interfacial adhesion between different materials is a topic of concern on stress distribution.

Concerning the interface between the FRC post and the resin cement, it was formerly demonstrated that satisfactory bond strength can be reached between the binary materials by creating covalent bonds between both substances (Heikkinen et al., 2009). The tenuous bond strength of resin cement might cause non-uniform stress distribution, resulting in consistent breakage of the resin cement, which leads to microleakage and unwanted results. SEM investigations in former studies specified that the critical fracture departed from the cement layer below the loading point. When the applied load increases, destruction spreads progressively in the supportive core substance, finally losing its supportive operation. When a radial crack originates from the bonded interface and spreads vertically, it creates a crown fracture, and the tooth structure absorbs the extra energy, resulting in disastrous failure (Aboushelib et al., 2007). Such a type of failure is irreparable and would directly affect the prognosis of the restoration.

Still, all documented failure loads in former studies (Salameh et al., 2008) were significantly higher than expected outcomes under typical masticatory cycles. Consequently, selecting a therapy choice that allows a larger fracture load and improved stress distribution can impact clinical performance. However, it is crucial to remember that if the bond strength can be improved, avoiding the unfavourable fractures related to restorative therapies would have a meaningful influence on decision-making when selecting methods for endodontic treatments.

### 6.3 Fatigue Behaviour (Study III)

The golden goal of root canal treatment is to clean and disinfect the endodontic system, the multiform three-dimensional tubular network. Erbium lasers can generate mechanical and thermal shock waves using low energy with very short pulses (photoacoustic phenomenon), resulting in excellent antimicrobial results (DiVito et al., 2012; Meire et al., 2022; Badami et al., 2024; Meire & De Moor, 2024; Fiegler-Rudol et al., 2025). The parameters applied in these protocols are below the ablation threshold for dentin. Many studies have inspected erbium lasers' impact on tooth surfaces during diverse dental therapies. It is essential to know the biomechanical properties of the dentin under distinct settings to choose the suitable mode of operation. Because cracking teeth is multifactorial and alternative therapies can have serious clinical results, the parameters applied in laser-assisted endodontics may significantly impact the mechanical properties of the dentinal structure. Different pulse durations, repetition rates, and distinct energy and power settings have been tested regarding cleaning properties of root canal dentin (De Moor et al., 2010; Meire et al., 2016; Badami et al., 2023; Brum et al., 2025).

Erbium lasers gained the FDA approval for cleaning, shaping, and enlarging the root canal system in 1990. The first endodontic laser tips were bare-ended with

straightforward emission, compared to the modern stripped, conical-shaped, radial-firing tips with 360° lateral emission. The distress with end-firing tips is caused by the high cavitation forces inducing the irrigant extrusion to the periapical part. Also, the desirable outcome of three-dimensional agitation in deep penetration of those elusive extensions would be without disadvantageous apical extrusion.

Diode lasers in the 810–980 nm wavelength range are widely used in dentistry to modify dentin surfaces and support bacterial decontamination during endodontic treatment. Importantly, when applied with recommended parameters (e.g., 940 nm and 980 nm), they do not negatively affect dentin flexural strength or fatigue resistance, making them safe for clinical use (Sippus, 2026). The primary interaction with dentin is photothermal, which enables surface modification that can improve adhesive performance. For example, lasers around 970 nm have been shown to increase microtensile bond strength and reduce premature adhesive failure, thus supporting longer-lasting restorations. In endodontics, their use also improves root canal disinfection when incorporated alongside conventional chemomechanical preparation. Taken together, these outcomes indicate that diode lasers enhance adhesion, strengthen dentin structure, and support infection control without compromising tooth mechanics (Holiel et al., 2026).

A previous study by Hmud et al. indicated that diode lasers operating at 940 and 980 nm can produce cavitation in liquids. Nevertheless, a collective misapprehension exists among the academic society that all incidences of bubble creation in water indicate cavitation. Consequently, some have misunderstood that such bubbles have prospective applications in eradicating debris and smear layers. A study revealed that diode-induced bubbles mature within a few seconds subsequent the initial laser pulse, contrasting with the cavitation mechanism of erbium lasers. The onset of bubble formation in erbium lasers transpires just microseconds prior to pulse initiation at the laser tip. Another notable divergence between solid-state and diode lasers is using low output powers with extended pulse durations, measured in milliseconds, by diode lasers. A noteworthy discrepancy between the two types of lasers can be observed in ‘the non-existence of shock waves in diode laser-induced bubble formation’, in contradiction to the rapidly collapsing cavitation bubble evidenced in the pulsed erbium laser (Hmud et al., 2010). The recording of such pressures can be facilitated by employing a high-speed camera.

Knowing the absorption characteristics of water is essential because within the NIR spectrum the 940 and 980 nm wavelengths have a higher water absorption than 810, 830 and 1.064 nm (Hmud et al., 2010). When hydrogen peroxide was used, the pattern was reversed. The explanation is the different absorption coefficients for water and hydrogen peroxide, with more considerable absorption at lower wavelengths in favour of hydrogen peroxide. Higher hydrogen peroxide concentrations may raise cavitation properties but might not be suitable because of

possible apical extrusion. The diode laser wavelengths 940 and 980 nm are of specific interest because both are near ideal water absorption and have a stronger absorption than other commonly used wavelengths like 810, 830, and 1.064 nm (Gutknecht et al., 2016).

The Study III evaluated the likely morphological alterations in dentinal structure that could distress fatigue strength after laser-assisted endodontic therapy. The current study layout is planned to compare intracanal irradiation with a 940 nm diode in dry circumstances to laser-activated irrigation in root canals with erbium lasers (Er:YAG 2.940 nm and Er,Cr:YSGG 2.780 nm). The optical properties of corresponding wavelengths are fundamental in defining their prospective applications and boundaries. Furthermore, it is even remarkable to distinguish their probable equivalent usage. Erbium wavelengths are intensely absorbed in water; hence, they are supreme for dental hard tissue removal. The 940 nm diode is excellent for bacterial decontamination because of a high absorption coefficient in melanin, haemoglobin, and oxyhaemoglobin (Martins et al., 2018). The pulse durations in Study III respected clinical obligations for endodontic techniques. Among erbium lasers, it is highly recognized that water is applied when cleaning the root canal system. The current research used no supplementary irrigants, only a saline solution. Even in this study, the indication was to eliminate the outcome of irrigants and examine the consequence of solely laser irradiation. A cavitation effect is generated by vapor bubbles inside the irrigant liquids; the bubbles expand and implode, causing a cleaning effect. Only a few studies have examined the generated pressure (Blanken et al., 2009; Hmud et al., 2010; López-Jiménez et al., 2015). It has been indicated that the divergences in the pressure magnitude generated in the root canal system during Er,Cr:YSGG with conservative LAI (Laser Activated Irrigation) setting at 0.75 W was considerably reduced than when applying 1.75 W, not depending on the tip model and irrigation liquids used (EDTA or NaOCl). The pressure was cumulative when approaching the apical portion (Peeters & De Moor, 2015).

Divergent to PIPS tips (Er:YAG), the RFTs (Er,Cr:YSGG) can be used for microbial sanitization in dry mode equivalent to the 940 nm diode, which is frequently used for deep disinfection of root canals (Vidas et al., 2020). The current study compared dentinal beams' fracture strength with non-irradiated beams in a 4-point bending test after laser treatment with diverse laser groups, Er:YAG, Er,Cr:YSGG, and 940 nm diode. No significant differences were discovered amid the different laser groups. The erbium laser groups exhibited marginally upper values.

Nevertheless, the fluences applied in customary endodontic therapies are under the ablation threshold. Respecting the proper settings for dental procedures in all situations is essential. Noticeably, the diverse laser delivery systems could be a key

factor in the present study and might underwrite the detected variations or equivalents in the outcomes. Former studies were able to show open tubules in erbium laser groups because of the cavitation effect. In present study the outcomes (SEM images) presented more open tubules related to the control group. Nevertheless, these results were not as extreme as in the former outcomes because of the testing setup. One limitation of our study was that the area is not completely as in a thin root canal. Likewise, the irradiated laser energy is transmitted throughout the dentin in an actual clinical condition, which does not correlate with the current mold test setup. Because of the cavitation result, part of the energy is gone over the edges due to the likely slight motion of the beams. The laser emission power will be weaker on the far end of the fibre tip, diverging from the parameters shown on the device's display, depending on the calibration factor (Arola et al., 2003; Martins et al., 2022). The used test arrangement was exceedingly standardised, with all groups exposed to processes in the unchanged root canal mould. This standardization divergences with actual clinical circumstances, as canal length, shape, and diameter will alter. Continuous irrigation was applied under the irradiation period. The laser beam is emitted laterally from a radial firing tip in the direction of the canal surface. In typical clinical situations, avoiding contact with the canal walls is impossible. This restricts the optimum locating of the fibre tip and subsequent liquid oscillation inside the root canal. Hence, the Er,Cr:YSGG and 940 nm diode are able to bear considerably larger wall contact. Additional discrepancy between procedures is the up-and-down motion of the handheld fibre tip. Differentially, the PIPS tip stays unmoved in the pulp cavity, liberated of intracanal tip placement. One limitation might be the synthetic configuration of the root imitating mould. This synthetic wall substance has a solid surface and a fashioned shape, allowing a traditional canal model, diverging from the normal anatomical structure of root canal. Furthermore, NaCl or distilled water was applied as the only irrigant diverging from commonly used NaOCl or EDTA. This was motivated by the fact, that current study series focused on the mechanical outcomes of laser irradiation, with all other generally applied irrigants being excluded (Sippus et al., 2023).

A recent study examined higher settings. When fluencies were applied above the ablation threshold, imitating a cavity floor on the dentinal beam surface, laser irradiation did not trigger any fading in the dentinal beams (Franzen et al., 2016). Likewise, when dentinal fatigue crack growth was experimented in human teeth, in replicated clinical situations, it was stated that slight flaws in teeth, about 250  $\mu\text{m}$ , will not drastically weaken the mechanical integrity, as the estimated fatigue lifetime will surpass that of the patient (Nalla et al., 2003; Staninec et al., 2009). Staninec et al. compared a free-running Er:YAG and a q-switch Er,Cr:YSGG, that laser irradiation produces mechanical and thermal destruction to the tooth structure in specific circumstances. However, it is remarkable that in this experimental study, the

q-switched Er,Cr:YSGG was applied dry and with very short pulse duration (Er:YAG 135  $\mu$ s against Er,Cr:YSGG 0.5  $\mu$ s), which does not associate with clinical settings. The applied mode of operation (wavelength, fluence, pulse duration, water/dry) marks the destruction caused to tooth structure (Staninec et al., 2009).

The Study III study evaluated the likely morphological alterations in dentinal structure that could distress fatigue strength subsequent laser-assisted endodontic therapy. The current study layout is planned to compare intracanal irradiation with a 940 nm diode in dry circumstances to laser-activated irrigation in root canals with erbium lasers (Er:YAG 2.940 nm and Er,Cr:YSGG 2.780 nm). The optical properties of respective wavelengths are essential to determining their prospective applications and boundaries. Furthermore, it is even remarkable to distinguish their probable equivalent usage. Erbium wavelengths are intensely absorbed in water and hydroxyapatite; hence, they are supreme for dental hard tissue removal. Diode lasers have been investigated because these pigments have a high absorption coefficient for such wavelengths, potentially allowing strong bactericidal effects either by directly targeting the pigmented membranes or by affecting the surrounding bacterial microenvironment. Hibst et al. (2010) demonstrated that high-power near-infrared (NIR) laser inactivation of bacteria occurs purely through photothermal effects, with no detectable photochemical contribution. Later studies, such as Martins et al. (2018), reported bactericidal effects with diode lasers; however, it remained unclear whether these effects were primarily due to heat generation.

The pulse durations in Study III respected clinical obligations for endodontic techniques. Among erbium lasers, it is highly recognized that water is applied when cleaning the root canal system. The current research used no supplementary irrigants, only a saline solution. Even in this study, the indication was to eliminate the outcome of irrigants and examine the consequence of solely laser irradiation. A cavitation effect is generated by vapor bubbles inside the irrigant liquids; the bubbles expand and implode, causing a cleaning effect. Only a few studies have examined the generated pressure (Blanken et al., 2009; Hmud et al., 2010; López-Jiménez et al., 2015). It has been indicated that the divergences in the pressure magnitude in the root canal system applying Er,Cr:YSGG with conservative LAI technique at 0.75 W was significantly lower than when applying 1.75 W, not depending on the tip model and irrigation liquids used (EDTA or NaOCl). The pressure was cumulative when approaching the apical portion (Peeters & De Moor, 2015).

The perfect tool for removing tissue should be selective and maintain the strength of the dentinal structure after the preparation. Near-infrared (NIR) use in endodontics remains a debated issue. NIR should be considered an adjunct rather than a replacement for cavitation-based irrigant activation techniques. The core of the laser controversy is that NIR alone cannot effectively substitute irrigant activation unless temperatures are increased to levels that risk damaging the periodontal tissues (Meire

et al., 2012). Yet, there is a concern about the usefulness and probability for tissue harm from increased temperature and the consequences, even to the bonding faces of the irradiated surfaces. Specific laser settings produce thermal and mechanical harm to the dental structure during irradiation. Meanwhile, other settings cause small or no peripheral harm. The level of peripheral damage in the irradiated tooth surface depends on the variables, including laser wavelength, pulse duration, fluence rate, and the applied amount of water. Cracks are frequently witnessed during the irradiation of dental hard tissues. Elastic solid waves are generated during short laser pulses, leading to ablation due to the brief thermal shock caused by the laser thermal expansion, heating, and recoiling of the products (Vogel & Venugopalan, 2003). Such stress waves transmit through hard tissue, feasibly producing cracks and fractures. The reflection of compressive thermoelastic pressures causes tensile stresses superficially on the tested dentin samples. The stress magnitude depends on the applied laser fluence, spot size, and pulse duration. An earlier study evaluated the fatigue crack growth ratio correlated to the density and orientation of dentinal tubules. They could firm that the dentinal tubule orientation would affect the crack growth. For a similar motivation, in the current study, all irradiated dentin beam surfaces were marked to detect the surface facing the root canal. This meticulous approach ensured the accuracy of our findings. Likewise, in the bending test, the specimens were placed so that the load was applied in the identical direction as the laser irradiation (Arola & Rouland, 2003).

Resin-dentin bonds have been examined in various studies like hydrolytic processes (Tjäderhane, Mehtälä, et al., 2013) or acids produced by biofilm (Arola & Reprogel, 2006; Spencer et al., 2010; ten Cate, 2006). Biofilm degradation has been stated to induce an expressive decrease in strength and fatigue resistance. The first investigation on the fatigue strength of the resin–dentin bonded interface following biofilm exposure was probably conducted in 2012. Earlier *in vitro* studies of the resin–dentin interface have been mainly directed by means of quasi-static loading and have not evaluated the degradation in mechanical properties influenced by oral microbes. The outcome was that exposure to biofilm initiated a meaningful reduction in strength and fatigue resistance compared to an equal time of water aging. The interfacial strength under quasi-static loading decreased by 50%, and the endurance limit fell by 30%. To compare, the evident endurance limits between coronal dentin and resin composite samples when tested in equal circumstances were 43 MPa (Arola & Reprogel, 2006) and 48 MPa (Mutluay et al., unpublished results), correspondingly. The presented results are more than three times larger than the interface between resin and dentin after water aging and more than four times larger than following exposure to biofilm (10 MPa).

The weakest link under cyclic loading is the resin dentin-bonded interface (Spencer et al., 2010), and exposure to biofilm additionally raises its sensitivity to

fatigue failure. Measuring the decrease in fatigue strength is a respected form of evaluation, but the decrease in consistency and life of the bonded interface has additional value to clinical practice. Studies commonly adopt a fatigue limit of  $1 \times 10^5$  cycles or less. When expecting 500 to 750 k masticatory cycles per year (Anusavice, 1996), the described above relates to oral function in under one year. If restorative dentistry aims to maintain lifetime oral health, then a more extended evaluation period for durability is needed (Mutluay et al., 2013). This finding could clarify our conclusion, where both erbium lasers got the uppermost deceptive endurance limits. The capability of erbium lasers to clean proficiently by photo-acoustic phenomena can destroy biofilm and, consequently, prevent the acid influence from biofilm degradation. This potential of erbium lasers to prevent acid influence, as affirmed by Hibst and Keller (1993), could significantly improve the outcomes of dental procedures, especially when compared to the negative consequences of ultra-short pulses using a q-switch laser (Staninec et al., 2009).

Due to diversities in bonding mechanisms (Goracci et al., 2005; Wrbas et al., 2007; Calixto et al., 2012), additional studies are necessary to evaluate if the favourable effect of laser irradiation could benefit etch-and-rinse and self-etch resin cement in bonding to intraradicular dentin.

# 7 Conclusions

Based on the series of studies presented in this PhD thesis, the findings were obtained under the specific conditions of the present investigations and should therefore be interpreted with consideration of these limitations. Consequently, the results may differ from those reported in other studies. The following conclusions can be drawn:

- I An Er:YAG laser, creating cavitation forces in the irrigant, either with PIPS or Preciso tips, did not improve the elimination of smear layer from dentinal tubules in the apical segment of a straight root canal when saline solution was used solitary as the irrigant.
- II Er:YAG and Er,Cr:YSGG laser irradiation procedures applied with unique end- and radial-firing tips promoted self-adhesive resin cement adhesion to intraradicular dentin. The integrity of bonded intraradicular interfaces was improved by laser irradiation with diverse protocols/tips, especially with the intra-cannally positioned radial-firing tip. Moreover, laser-activated irrigation created improved bond strengths at the demanding apical root area. These enhancements in intraradicular bonding implementations emphasise lasers' usefulness in creating more enduring cement-dentin interfaces, which may diminish clinical debonding of fibre posts subsequent endodontic treatments and restorations.
- III Within the limitations of this study, it can be concluded that the 940nm diode laser, supplementing Er:YAG and Er,Cr:YSGG lasers employing the tested protocols, did not compromise the fatigue strength of root dentin. Subsequently, these lasers serve as a valuable adjunct to contemporary root canal deep-cleaning protocols. Additionally, the tested laser-assisted endodontic applications did not alter or damage the tooth structure. All the findings are under the conditions of the present investigation.

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