



Application of Dental Lasers in the Field of Endodontics: A Review of Literature

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Abstract

The present study aims to provide readers with the influence of various types of dental lasers in endodontics, along with their advantages and disadvantages. A complete query was carried out on PubMed, Google Scholar, Embase, and Scopus databases, and the studies published during 2015-2024 were collected using the keywords "Laser," "Endodontics," "Disinfection," "Vital Pulp therapy," and "Regenerative Endodontic Treatment." After applying appropriate inclusion and exclusion criteria, 86 relevant articles focused on the application of dental lasers in endodontics were selected and evaluated. Based on the evaluated studies, probably the most significant advancement of dental lasers is in optimizing the treatment outcome of root canal therapy *via* enhanced disinfection of root canals. Moreover, various research has shown that dental lasers can also aid in diagnosing vitality of pulp, vital pulp therapy, apiectomy, regenerative treatments, pain management treatment after root canal therapy, access cavity preparation, sterilization and irrigation of root canals, treatment of periapical lesions, removing excess materials and broken instruments in canals, and prompting the healing process after root canal therapy. As evidenced by the obtained results, diode and erbium lasers have the most applications in endodontics with the lowest side effects. Nonetheless, all dental lasers face multiple limitations, including producing noticeable thermal changes and smoke and damaging surrounding structures at the emission site, which question their safe usage in clinical practice. Therefore, dental lasers' newest advancements in dental procedures require further scientific work in the future.

Keywords: Disinfection; Endodontics; Laser; Regenerative Endodontic Treatment; Vital Pulp Therapy

Introduction

A laser is an acronym for Light Amplification by Stimulated Emission of Radiation, which refers to a technology that enhances the production of photons through stimulated emission. Essentially, lasers convert light from various wavelengths, including visible, infrared, and ultraviolet, into a single, monochromatic, coherent wavelength, creating concentrated beams of energy and heat [1, 2]. These unique characteristics make lasers invaluable tools in a wide range of scientific, medical, and industrial applications, including dentistry [3].

The theoretical foundation for laser technology dates back to 1917, when Albert Einstein first proposed the concept of light amplification. However, it was not until 1958 that Charles Townes and Arthur Schawlow formally outlined the principles required for laser operation. Building upon these theories, Theodor Maiman successfully demonstrated the first practical laser in 1960, utilizing a pink sapphire crystal as the medium. Following this breakthrough, lasers began to be applied in various fields, including medicine, with dentistry being one of the earliest adopters. Laser technology was introduced to clinical dentistry in the 1970s, initially with CO₂ and Neodymium-doped Yttrium Aluminum Garnet (Nd: YAG) lasers.



As scientific research advanced, the variety and applications of lasers in dental practice grew, and brand-new laser types, including Erbium: YAG (Er: YAG), Erbium Chromium: Yttrium Scandium Gallium Garnet (Er, Cr: YSGG), diode lasers, Helium-Neon (He: Ne) lasers, and Argon lasers were introduced into dental treatments [4, 5]. The application of lasers in endodontics, particularly in root canal therapy, began in 1971 when Weichman and Johnson pioneered the use of a CO₂ laser to seal the apical foramen, marking a significant milestone in the field of endodontics [6, 7]. Since then, various other laser technologies have gained widespread acceptance in endodontic practice [8].

Root canal therapy is a critical procedure designed to clean, disinfect, and seal the root canal system to prevent infection and treat apical periodontitis, thereby preserving the tooth's health and functionality [9]. Achieving optimal outcomes and long-term success in this treatment is essential. Therefore, lasers have become integral tools in endodontics, offering a variety of applications that enhance the effectiveness of root canal therapy [4, 8]. Although numerous studies have highlighted the positive effects of lasers, such as their anti-inflammatory, analgesic, and tissue-regenerating properties, there are still challenges to their widespread adoption in clinical practice. High equipment costs and ongoing uncertainty regarding the overall effectiveness of lasers as a primary treatment modality contribute to debates about their comprehensive use in dentistry [4, 6].

On the other hand, given the broad array of laser types available for endodontic procedures, understanding the specific properties of each laser, including wavelength, energy settings, and application, is crucial for optimizing their clinical use. This knowledge, derived primarily from laboratory research, can help improve clinical outcomes by ensuring the correct selection of laser type and energy dosage. In fact, in many clinical cases, treatment failures are not due to the inherent inefficiency of the laser, but rather to improper laser selection or incorrect energy application [10, 11]. Therefore, the objective of this study is to explore and compare the application of various laser types at different endodontic-related treatments, along with their respective advantages and disadvantages.

Materials and Methods

In this literature review, a manual search was conducted across multiple databases, including PubMed, Google Scholar, Embase, and Scopus. The search strategy employed Boolean descriptors and operators and was restricted to articles published in English between January 2015 and December 2024. For PubMed, equivalent MeSH terms were also applied where available. The Boolean search terms were as follows:

("Endodontics"[Mesh] OR "Root Canal Therapy"[Mesh] OR "root canal" OR "root canal treatment" OR "root canal disinfection" OR "root canal preparation" OR "endodontic surgery" OR "apicoectomy" OR "vital pulp therapy"[Mesh] OR "pulp capping" OR "pulpotomy" OR "regenerative endodontics" OR "root canal retreatment" OR "periapical diseases"[Mesh] OR "periapical periodontitis" OR "dental pulp diseases"[Mesh]) AND

("Lasers"[Mesh] OR "Laser Therapy"[Mesh] OR "Low-Level Light Therapy"[Mesh] OR laser OR "laser therapy" OR "diode laser" OR "Er: YAG laser" OR "Nd: YAG laser" OR "erbium laser" OR "photodynamic therapy" OR PIPS OR "photon-induced photoacoustic streaming" OR SWEEPS OR "shock wave enhanced emission photoacoustic streaming") AND

("Treatment Outcome"[Mesh] OR efficacy OR effective OR "smear layer" OR disinfection OR "bacterial reduction" OR "postoperative pain"[Mesh] OR "pain management" OR "wound healing"[Mesh] OR "apical seal" OR "debridement" OR "instrument removal" OR "healing" OR "success rate")

The searches were conducted from January to March 2025. The initial number of records retrieved was: PubMed ($n=2961$), Google Scholar ($n=2077$), Scopus ($n=565$), and Embase ($n=411$), giving a total of 6014 unique records. Subsequently, the Rayyan software was used to remove duplicates, and 4253 articles entered the screening phase. In the screening phase, first, all the articles were evaluated based on the topic of the article and subject of interest, the keywords, and the inclusion and exclusion criteria by all authors. Any discrepancies between reviewers during the screening and eligibility assessment phases were resolved through discussion. If consensus could not be reached, a senior author (Author 2, with expertise in dental lasers) made the final decision.

The inclusion criteria in this research were the year of publication and the relevance of the subject, and the aims of the articles to the present research. The exclusion criteria included articles with unrelated information and topics, articles published before 2015, and case reports. According to the mentioned criteria and keywords, 754 English-written articles were selected and reviewed.

After the screening phase, the evaluation of the eligibility of studies was conducted by all authors. In the beginning, a specialized individual in the field of dental lasers (Author 2) investigated the accuracy and reliability of data regarding laser technology. In this phase, 302 articles that lack methodological clarity on lasers' application in endodontic procedures were eliminated. In the next phase, the other authors evaluated the value of the information presented in the articles, the method of

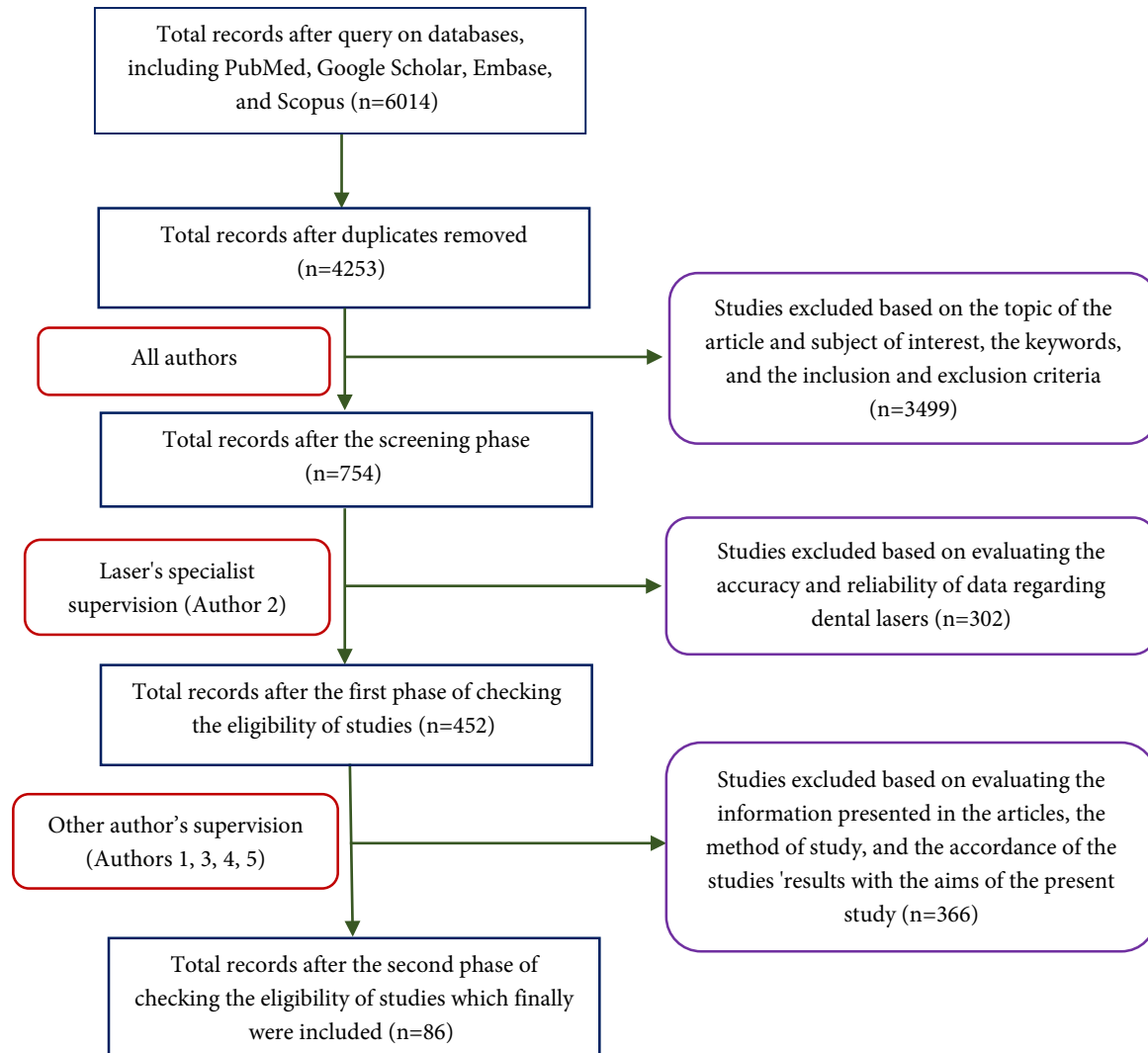


Figure 1. The study's methodology

study, and the consistency of the studies' results with the aims of the present research. After this precise review, 234 articles were excluded based on the absence of any information regarding the possible side effects of lasers in endodontic treatments. Moreover, 132 articles were excluded due to a lack of information on comparing the laser application with the gold standard method in endodontic treatments. Ultimately, 86 articles entered the study. In Fig. 1, the study's methodology is presented.

Result

The search strategy yielded a selection of 86 articles, comprising 49 from PubMed, 18 from Google Scholar, 3 from Embase, and 16 from Scopus. After a comprehensive review of the literature, it was observed that 18 articles were focused on the overall concept of dental lasers and their structure, and 8 articles discussed their

various types. Subsequently, 60 other articles illustrated the application of dental lasers in different branches of dentistry. Out of the 60 articles assessing lasers' application in various procedures, 17 articles were regarding cleaning and disinfection of the root canal system, 6 articles were about the removal of debris and smear layer, 3 articles were related to non-surgical treatment of periapical lesions, 1 article was regarding apical seat, 11 articles were related to post-treatment pain management, 3 articles were about pulp vitality diagnosis, 7 articles were related to vital pulp therapy, 2 articles were about access cavity preparation, 1 article was regarding regenerative treatments, 3 articles were related to root canal retreatment, 1 article was about the removal of fractured instruments from the canal, 2 articles were related to the removal of fiber post from the canal, 2 articles were regarding alleviation of nausea, and ultimately 1 article discussed the application of lasers in sterilization of instruments.

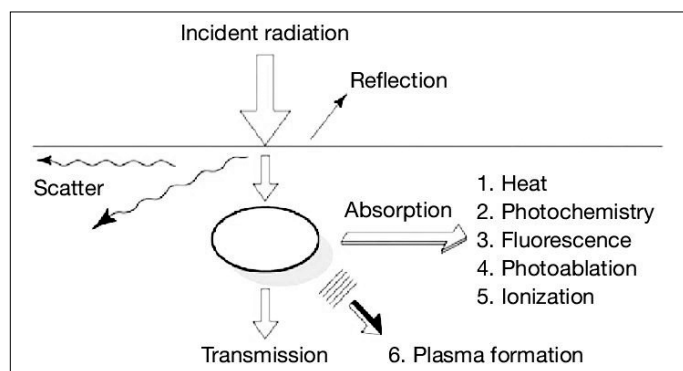


Figure 2. Types of laser-tissue interactions

Discussion

The introduction of dental lasers into clinical practice has significantly improved the performance and precision of dental procedures, leading to better treatment outcomes and enhanced effectiveness [12]. However, various studies emphasize the importance of dentists possessing a thorough understanding of laser technology, including the principles behind how lasers work, how to determine appropriate radiation doses, and how to select the appropriate laser for various dental applications. [12, 13]. Accordingly, this section will first explore the fundamental principles of laser technology and its types, followed by a comprehensive discussion on their specialized applications in the field of endodontics.

Laser structure and types

Lasers function by harnessing light, a form of electromagnetic radiation that travels at a constant speed of 300,000 km/s. Light is emitted as waves, and its basic unit is the photon [14]. The process of laser light generation initiates when an atom absorbs energy, causing it to become excited. This excitation prompts the atom to emit a photon. The emission of one photon then stimulates the emission of additional photons, leading to a cascade effect. This repetitive process continues until a collection of photons produces coherent, monochromatic light, known as laser light. The wavelength of the emitted photons, which is crucial in determining the type and application of a particular laser, is influenced by the energy of the electron when the photon is emitted. Different wavelengths are suited to different applications, with specific wavelengths being more effective for certain dental procedures, particularly in endodontics. For instance, lasers that produce wavelengths in the ultraviolet region of the electromagnetic spectrum have shown promise in various endodontic treatments [15-17].

Several factors, including the way dental lasers interact with tissue (Fig. 2), wavelength, physical structure, type of medium, and the tissues on which they are applied, are notable in their categorization [18]. In Table 1, an overview of the characteristics of different lasers is provided [18-23].

Low-level laser therapy

Low-level laser therapy (LLLT), or photobiomodulation (PBM), is a non-thermal treatment that utilizes low-power lasers, typically under 0.5 W, within the red to near-infrared light spectrum. Its biostimulatory effect originates from the absorption of light by mitochondrial chromophores, leading to enhanced cellular energy production and the activation of pathways that reduce inflammation and oxidative stress. This mechanism underpins its primary therapeutic benefits of analgesia and anti-inflammatory action [24].

In endodontic practice, PBM serves as a valuable adjunct for enhancing patient comfort and improving treatment outcomes. Common applications include managing post-operative pain following root canal procedures, accelerating the healing of periapical tissues, and aiding in objective pulp vitality testing through laser Doppler flowmetry. There is also growing interest in its potential to support vital pulp therapy by modulating the inflammatory response in the dental pulp [25].

A critical distinction must be made between PBM and antimicrobial photodynamic therapy (PDT). In PDT, a low-power laser (often a diode laser) is used as a cold light source to activate a photosensitizing drug. The power settings for PDT are typically higher than those used in LLLT (often ranging from 100 mW to several Watts), but are applied for a very short duration to avoid thermal effects [5, 6].

While both involve laser light, PDT is primarily a disinfection technique. This method relies on applying an exogenous photosensitizer dye to the root canal system, which, when activated by light, generates cytotoxic reactive oxygen species to eliminate microorganisms. In contrast, PBM operates without any external agent, using low-level light to biostimulate native tissue repair and reduce inflammation, making it a complementary therapy for managing the host response rather than a primary antimicrobial protocol [5, 25, 26].

Lasers' application in the field of endodontics

Cleaning and disinfection of the root canal system

Preparation of the root canal system by removing tissues, debris, and by-products of microorganisms creates space for irrigating solutions and antibacterial agents to disinfect the canal. This process establishes a bacteria-free environment for placing root canal filling materials [6, 27]. Despite the introduction of various

Table 1. A summary of dental lasers' characteristics

Laser	Wavelength	Indications	Specific features	Advantages	Disadvantages
CO ₂	10600 nm	Soft tissue	Easy absorption by enamel and dentin Biocompatibility Tissue vaporization	High homeostasis power Disinfection Low cost Optical biocompatibility	Temperature changes Incompatibility with optical fibers Large size of the device Sensitive to environmental conditions Difficult storage conditions
Nd: YAG	1064 nm	Soft tissue	High biocompatibility Energy dispersion and penetration into adjacent biological tissue Coagulation effects	High homeostasis power Disinfection Optical biocompatibility Minimal thermal damage	Temperature changes Large size of the device High cost Low penetration depth Limited wavelength Brittle and vulnerable Sensitive to environmental conditions
Er: YAG	2936 nm	Soft tissue Hard tissue	Easy absorption by hydroxyapatite crystals Water vaporization due to slight temperature increase Removal of hard tissue	Weak to moderate hemostasis Disinfection Optical biocompatibility Minimal temperature changes	Large size of the device High cost Limited penetration depth High skill requirement Side effects such as swelling and redness Inadequate absorption by tissue Accessibility limitations Need for anesthesia
Er; Cr:YSGG	2780 nm	Soft tissue Hard tissue	Easy absorption by hydroxyapatite crystals Water vaporization due to slight temperature increase Removal of hard tissue High cutting ability with water spray without increasing temperature	Weak to moderate hemostasis Disinfection Optical biocompatibility Minimal temperature changes	Limited penetration depth High cost Large device size Requires high skill level Side effects such as swelling and redness Insufficient tissue absorption Access limitations Need for anesthesia
Diode	810-980 nm	Soft tissue	High penetration Effect on microorganisms within dentinal tubules	Weak to moderate hemostasis Disinfection Optical biocompatibility Low cost Small device size	Limited wavelength Heat generation Lower output power Low beam quality and low accuracy Divergent radiation Limited penetration depth Tissue damage potential
Nd: YAP	1340 nm	Soft tissue Hard tissue	High absorption by water, metals, and dark materials	Effective disinfection High accuracy Minimal thermal damage Hemostasis Reduced need for chemical detergents Decreased pain after treatment	High cost Limited penetration depth Requires high skill level
Ar	488-514.5 nm	Soft tissue	Selective absorption Absorption by melanin and hemoglobin	Effective disinfection High accuracy Minimal thermal damage Hemostasis Necrotic tissue destruction	High cost Limited penetration depth Requires high skill level

CO₂: carbon dioxide, Nd:YAG: neodymium-doped yttrium aluminum garnet, Er:YAG: erbium-doped yttrium aluminum garnet, Er,Cr:YSGG: erbium, chromium-doped yttrium, scandium gallium garnet, Nd:YAP: neodymium-doped yttrium aluminum perovskite, Ar: argon

tools for cleaning and shaping the root canal system, recent studies have highlighted the high antibacterial efficacy of laser irradiation. Furthermore, it has been observed that both low-power and high-power lasers can be used for canal disinfection, with the effectiveness of these lasers being directly related to the radiation dose and energy level [28, 29].

In summary, lasers can eliminate microorganisms within the canal through three different mechanisms. In the first method, known as Laser-Assisted Disinfection (LAD), high-power lasers are used to eradicate microorganisms in the canal. Among high-power lasers, the Nd: YAG laser appears to have a superior ability to eliminate root canal bacteria due to its higher penetration depth in dentin. However, this high penetration depth facilitates the transfer of thermal energy beyond the root canal system, which can pose a significant risk of causing thermal necrosis to the periodontal ligament and surrounding bone. Therefore, the application of LAD is limited due to safety concerns [30].

Studies on the efficacy of Nd: YAG laser in root canal disinfection present conflicting results [7, 31]. For instance, a 2016 review article demonstrated that the Nd: YAG laser has only partial direct bactericidal effects on *Escherichia coli* (*E. coli*) and *Enterococcus faecalis* (*E. faecalis*) bacteria within the canal [7]. In contrast, a clinical study by Granevik Lindström *et al.* [31] showed that when the Nd: YAG laser is applied in pulsed mode with 1.5 W power, 15 Hz frequency, a speed of 2 mm per sec, and repeated four times at 20-sec intervals, it does not significantly reduce bacteria in the canal more effectively than canal irrigation with 1% sodium hypochlorite [31, 32].

The latter study indicated that the primary antibacterial effect of the Nd: YAG laser is due to its photothermal effect. Since microbial agents exhibit resistance to heat, the temperature increase induced by this laser is insufficient to eradicate infectious agents. Instead, it risks damaging the periodontium and surrounding bone. Due to the thermal damage caused by most high-power lasers, the LAD method using high-power lasers is no longer recommended for root canal disinfection [31].

In addition to the Nd: YAG laser, some studies have investigated using diode lasers to eliminate microbial agents within the canal. These studies have reported conflicting results regarding their effectiveness [33-35]. For instance, a study by Pelozo *et al.* [34] illustrated that when a diode laser was applied in pulsed mode at 1.5 W power and 100 Hz frequency for 20 sec after irrigating the canal with normal saline, the bacterial load immediately after laser application was reduced by 42.44% compared to the placebo group, which received only normal saline. In contrast, a study by Mishra *et al.* [35] showed that when

a root canal was disinfected using a diode laser first in pulsed mode and then in continuous mode at 3 W power for 20 sec, and the results were compared with the gold standard method of irrigating the canal with 5.25% sodium hypochlorite for 5 min, the continuous diode laser method was more effective than the gold standard method. Moreover, the continuous technique was more effective than the pulsed technique in cleaning the root canal [35]. Based on findings from various studies, it can be concluded that the diode laser, when used in continuous mode, can serve as an adjunct tool alongside the gold standard method for irrigating and disinfecting the root canal [33].

In the second method, known as Laser-activated irrigation (LAI), the Er, Cr: YSGG lasers are used for canal disinfection by activating irrigants. The efficacy of this technique is fundamentally based on the high absorption of its wavelength by water and hydroxyapatite. In the presence of NaOCl, this absorption mechanism is critical; the laser energy is rapidly converted to kinetic and thermal energy within the irrigant itself [30].

The procedure involves the insertion of a specialized, flat-ended, radial-firing fiber tip into the coronal third or pulp chamber. The tip mustn't be inserted deep into the canal to prevent contact with the dentinal walls and to allow for unimpeded fluid movement [36].

Upon activation, the laser energy causes rapid vaporization of the water content in the irrigant, generating powerful vapor bubbles and secondary cavitation effects. This creates vigorous, three-dimensional streaming of the sodium hypochlorite throughout the entire root canal system. The primary mechanisms of action are therefore the physical dislodgement of biofilm and debris through this acoustic streaming and the enhanced chemical efficacy of the rapidly moving NaOCl. However, it is important to note that the effectiveness of this fluid dynamics is most pronounced in the main canal lumen [36].

Photon-induced photoacoustic Streaming (PIPS) is another method being used to eliminate bacteria similar to LAI. In this method, Er: YAG lasers are utilized to enhance the movement of irrigants within the canal and apply physical force to the canal walls. Nonetheless, the laser tip is positioned in the pulp chamber, ensuring that the canal walls and periapical tissues remain unaffected. Additionally, studies have reported that the cleaning and disinfection of the root canal in the PIPS method is more effective compared to the LAI method [30, 37].

Another laser application similar to the two previous methods is "shockwave enhanced emission photoacoustic streaming" (SWEPS). This method also uses Er: YAG lasers for canal disinfection, like the previous method. In contrast to PIPS,

which uses single-pulse energy (50 microsec), SWEEPS employs double-pulse energy (25 microsec). Thus, in the SWEEPS method, the presence of two separate pulses with a shorter time interval leads to a more substantial explosion of water particles within the canal, generating a stronger photoacoustic flow [30, 32]. Nevertheless, it should be noted that there is some disagreement in the literature regarding the effectiveness of the PIPS and SWEEPS methods in cleaning and disinfecting the root canal system [32, 38, 39].

In the study by Kosarieh *et al.* [40], it was observed that when the Er: YAG laser, with a power of 0.3 W, energy of 20 millijoules, and frequency of 15 Hz, was applied using both the PIPS and SWEEPS methods for 50 microsec per pulse to clean the root canals of 60 single-rooted teeth, the penetration depth of the dye in the apical third of the root was greater with the PIPS method than with the SWEEPS method. In fact, this study reported that the PIPS technique was superior to SWEEPS for root canal cleaning in endodontic treatments. However, the study by Mancini *et al.* [41] reported that when the Er: YAG laser, with similar power, energy, frequency, and application time as in the previous study, was used with both the PIPS and SWEEPS methods to clean the root canals of 85 mandibular premolars, there was no significant difference in the disinfecting effectiveness between the two techniques. Even though it can be assumed that the type of tooth selected for the study might be the reason behind the discrepancy between the two studies, further research is required in this area to clear this matter [40, 41].

In contrast to the controversy seen among studies regarding PIPS and SWEEPS efficacy in root canal disinfection, it seems that these methods can be useful in the removal of residual calcium hydroxide [38, 39]. For example, in an in-vivo study conducted by Yang *et al.* [38] on 40 mandibular molars, it was observed that the use of an Er: YAG laser in pulsed mode (0.3 W power, 15 Hz frequency, and 20 mJ energy) inside the pulp chamber for 30 sec, utilizing the PIPS or SWEEPS technique, achieved superior removal of residual calcium hydroxide compared to conventional canal irrigation with 1.5% sodium hypochlorite, particularly in the cervical third of mesial canals. The study further demonstrated no significant difference in the efficacy of the PIPS and SWEEPS techniques in canal cleaning. However, it was noted that even the combination of laser application with conventional irrigation could not completely eliminate calcium hydroxide from the canal [38].

Similarly, Usta *et al.* [39] confirmed these findings, reporting that the application of an Er: YAG laser (0.3 W power, 15 Hz frequency, and 20 mJ energy) inside the pulp chamber for 30 sec using the SWEEPS technique, in conjunction with conventional

irrigation with 1.5% sodium hypochlorite and saline, yielded optimal results in the removal of calcium hydroxide and antibiotic paste residues during regenerative treatments [39]. Thus, the use of Er: YAG lasers in combination with conventional irrigation methods is now recommended for the effective removal of residual materials from the canal [38, 39].

The third laser-assisted method for root canal cleaning and disinfection is PDT. In this method, a light-absorbing substance called a photosensitizer is placed inside the root canal and activated using a low-intensity light source. Following this activation, reactive oxygen species are generated, which have the capability to eliminate microorganisms without causing toxicity to normal cells [42]. Various studies have shown that this method is primarily used for disinfecting the canals of immature teeth in regenerative treatments, yielding favorable results [30, 43].

In a clinical trial conducted by Emam *et al.* [43], it was observed that when a diode laser was used to activate the photosensitizer inside the canal in combination with the placement of calcium hydroxide during regenerative treatment of immature single-rooted teeth, the increase in canal length and overall canal cleaning were significantly greater compared to photodynamic therapy alone or the placement of calcium hydroxide alone, in a follow-up phase of 9 months to 1 year [43].

Removal of debris and smear layer

The smear layer is a layer composed of organic and inorganic materials that is formed during the mechanical preparation of the root canal. The smear layer acts as a physical barrier, preventing the penetration of disinfectants and medicaments into dentinal tubules and interfering with the adhesion of sealers. Moreover, residual bacteria in dentinal tubules can become sealed under the smear layer after canal preparation, potentially leading to future endodontic lesions [44]. Therefore, the removal of the smear layer is an integral part of endodontic treatment and is commonly achieved using a chelating agent such as EDTA. However, studies have shown that EDTA is not capable of completely removing the smear layer. Furthermore, since irrigation solutions only penetrate approximately 1.5 mm beyond the syringe tip in the root canal, chelators may be ineffective in removing the smear layer in the apical regions of the canal [45]. Consequently, lasers have been proposed as an alternative for achieving complete removal of the smear layer [44].

Among the most commonly used lasers for smear layer and debris removal are erbium-family lasers. Nonetheless, various studies have reported conflicting results regarding their effectiveness compared to the gold standard method [46-48]. For instance, in a study by Kourti *et al.* [47], it was observed that when Er, Cr: YSGG laser with a 200-micrometer tip (power:

1.25–2.5 W, energy: 25–50 mJ, frequency: 50 Hz, pulse duration: 140 microsec) and Er: YAG laser with a 300-micrometer tip (power: 0.75–2 W, energy: 30–80 mJ, frequency: 25 Hz, pulse duration: 300 microsec) were separately used to remove the smear layer from the mesial roots of mandibular first molars, these lasers demonstrated higher efficacy compared to the placebo group, which received 5 mL of 17% EDTA for 60 sec, 5 mL of 5% NaOCl, and 5 mL of distilled water. However, the study also noted that in curved canals and the apical third of the canal, where laser tips could not effectively reach, the use of chelating agents was still necessary for smear layer removal. Furthermore, the study showed no significant difference in the performance of the two lasers and concluded that increasing the power and pulse energy of the laser does not result in more effective smear layer removal [47].

In contrast to the results of the previous study, Habshi *et al.* [48] reported that when Er: YAG laser with two types of tips (flat and tapered) was applied at a frequency of 15 Hz and a pulse duration of 15 microsec for smear layer removal in single-rooted teeth, the results were inferior to the control group. The control group received alternating irrigation with 3 mL of 3% NaOCl and 3 mL of 17% EDTA, followed by 10 mL of distilled water. Specifically, the authors noted that while the flat tip demonstrated better smear layer removal, none of the laser methods achieved results comparable to the gold standard. Additionally, the study observed that using the tapered tip resulted in leaving more debris behind [48].

Due to the contradictory findings regarding the efficacy of erbium-family lasers in removing debris and smear layers, researchers have explored the use of diode lasers [46]. For instance, in a study by Karunakar *et al.* [49], it was observed that continuous application of a diode laser at 2 W significantly improved smear layer removal in the apical third of single-rooted teeth compared to canal irrigation with 5.25% NaOCl and 17% EDTA for 1 min. Based on the results of various studies, it can be concluded that erbium-family lasers are insufficient for removing smear layers and debris, particularly in the apical third of the root, due to the large diameter of their tips. In contrast, diode lasers, with their smaller tip diameter and minimal thermal effects, appear to be a more suitable option for smear layer and debris removal in this region. However, it is important to note that lasers alone are not adequate for smear layer and debris removal and must be combined with the gold standard protocols [46–49].

Treatment of periapical lesions

The healing of periapical lesions depends on various factors, including the preparation, shaping, and filling of the canal.

However, lasers have recently been recognized as a valuable tool for eliminating intracanal bacteria and contributing significantly to the resolution of periapical lesions [50]. Multiple studies have employed different types of lasers for this purpose and reported similar outcomes [50–52]. For instance, Shaheed *et al.* [51] demonstrated that when Er, Cr: YSGG laser was used at 1.25 W to remove the smear layer and subsequently at 1 W three times at a speed of 1–2 mm/s for canal disinfection, it resulted in more effective healing of periapical lesions compared to conventional canal irrigation with sodium hypochlorite [51]. Similarly, a study by Dalaei Moghadam *et al.* [52] showed that diode lasers, applied in pulsed mode at 2 W for 20 sec with four repetitions at a speed of 2 mm/s, exhibited high efficacy in eliminating intracanal bacteria [52]. Consistent findings were also observed in another study using an Nd: YAG laser in pulsed mode at 1 W and a frequency of 66 mJ/pulse for 1 sec, demonstrating comparable bacterial reduction [50].

Improving the quality of apical seal

Achieving an adequate apical seal is one of the critical factors for the success of endodontic treatment. Recent studies have indicated that laser-assisted canal irrigation can significantly enhance the quality of the apical seal [53]. For instance, an *in vitro* study conducted by Khoshbin *et al.* [53] demonstrated that the use of either a diode laser or an Nd: YAG laser for intracanal disinfection, in conjunction with a conventional canal irrigation method using sodium hypochlorite, resulted in significantly improved apical sealing. In this study, diode lasers were applied in continuous mode at 0.1 W, with a speed of 2 mm/s and four repetitions, each separated by a 20-sec interval. On the other hand, Nd: YAG lasers were employed at 2 W, with an energy density of 50 mJ/s, a frequency of 15 Hz, a speed of 2 mm/s, and four repetitions at the same interval. This study also revealed that the type of sealer had no significant effect on the quality of the apical seal, whereas diode lasers produced better results compared to Nd: YAG lasers. These findings can be explained by the fact that the Nd: YAG laser completely seals the dentinal tubules, whereas the diode laser relatively occludes the tubules. Therefore, the sealer cannot penetrate the tubules in the first situation, and thus, a greater apical microleakage occurs [53].

Post-treatment pain management

The primary reason for post-endodontic treatment pain is acute inflammation of the periapical tissues, which is typically managed with non-steroidal anti-inflammatory drugs (NSAIDs) [54]. However, recent studies suggest that lasers, especially Nd: YAG lasers, can serve as an effective adjunct for post-treatment pain management [55]. For instance, in a study by Nabi *et al.* [56], the analgesic effect of low-level lasers (50 Hz) applied to

both buccal and lingual surfaces of the periapical area for 3 min post-treatment was compared to oral administration of 400 mg ibuprofen one h before treatment. The results indicated no significant difference between the two groups during the first h post-treatment. However, after 12 h, the laser group showed a noticeable reduction in pain and was proposed as a suitable alternative, particularly for patients prone to gastrointestinal side effects of ibuprofen. Nonetheless, the study concluded that combining ibuprofen with low-level laser therapy provided the most effective pain relief [56].

The analgesic effect of lasers has been discussed in various studies [54, 57]. It seems lasers reduce pain through mechanisms such as lowering pain mediators like bradykinin and histamine, reducing inflammation by suppressing prostaglandin E2 and interleukin-1 beta, increasing endogenous endorphin production, and reducing oxidative stress, edema, and bleeding. In one study, the optimal dose for pain relief was identified between 0.3 to 19 J/cm² [54].

Aside from Nd: YAG lasers, diode lasers are being suggested for pain reduction after endodontic treatments. One study specifically compared two common methods of applying diode lasers for post-endodontic pain relief. In the first group, the laser was applied perpendicularly to the buccal and lingual surfaces, while in the second group, the laser was directly introduced into the canal for irradiation. The results demonstrated that during the first 24 h, the buccal and lingual surface application was more effective in reducing pain. However, after 48 h, no significant differences were observed, and both methods were equally effective [58]. These findings align with studies by Mandana Naseri *et al.* [59] and Toopalle *et al.* [60], which indicated that laser application on both buccal and lingual surfaces achieves superior analgesic effects compared to unilateral laser application [58-60].

Most studies have reported that among low-level laser types, diode lasers, due to their advantages including multifunctionality, affordability, high absorption by water, and low absorption by dental tissue, can operate precisely and selectively. Additionally, when used in a pulsed mode, they can effectively reduce post-treatment pain and improve the healing of the periapical area by preventing thermal damage [61-63]. However, this result contrasts with the findings of the study by Tunc *et al.* [64]. In this study, the first group used an Nd: YAG laser with a frequency of 15 Hz, an energy density of 100 mJ/s, and a power of 1 W, which was inserted 1 mm shorter than the working length into the canal for 5 sec. This process was repeated 4 times at 20-sec intervals. In the second group, a diode laser with similar energy density, power, and frequency to the

first group was applied for the same duration and working length. In both groups, the visual analog scale (VSA) was used to measure pain at 12-, 24-, 48-, and 72-h post-treatment. The authors of this study reported no significant difference in post-treatment pain control between the Nd: YAG and diode lasers in vital and non-vital teeth, except for the 48-h period after treatment in vital teeth, where the Nd: YAG laser showed better results [64]. Therefore, it can be concluded that there is still no certainty regarding the superior effectiveness of Nd: YAG or diode lasers in alleviating post-endodontic pain, and further studies are needed in this area [61-64].

Pulp vitality diagnosis

The diagnosis of pulp vitality following traumatic events is especially crucial in children, whose root apices have not yet fully closed. In other words, preserving pulp vitality in children can lead to continued growth and development of the tooth, thereby maintaining its function. Various diagnostic methods, such as thermal and electrical tests, have been proposed for this purpose. However, it has been observed that in the early phase following trauma, known as the shock phase, children may respond incorrectly to sensory tests or may show no response at all. Moreover, the child's lack of cooperation during this phase can lead to misdiagnosis by the dentist. Therefore, laser Doppler flowmetry is recommended for an accurate diagnosis of pulp vitality [65].

Laser Doppler flowmetry is an accurate, non-invasive, and repeatable method for assessing pulp blood flow using He-Ne or diode lasers. Unlike traditional vitality tests, which assess the response of sensory fibers within the pulp and often result in a high rate of false positive and false negative results, the true vitality of the pulp in this method is determined by its vascular condition, providing more accurate and reliable results. Nonetheless, it should be noted that this method cannot be used in patients with systemic conditions such as hypertension, anemia, or other hematological issues. Additionally, limitations such as long diagnostic times, the need for specialized equipment, and the restriction of application in molar teeth with thick dentin and enamel limit the routine usage of these lasers [66].

Considering the reported limitations of electrical pulp vitality tests and laser Doppler flowmetry, a study by Lee *et al.* [67] was conducted to compare the accuracy and specificity of these two methods in diagnosing pulp vitality after traumatic incidents. The study reported that both methods had 100% sensitivity, but the accuracy and specificity of the electrical method were considerably lower than those of the laser Doppler flowmetry method. In this study, a laser with an infrared wavelength of 830 nm, a frequency of 20 Hz, and a scanning range of 6.6×5.5 cm was used. The results indicated

that laser Doppler flowmetry could reliably be used for pulp vitality diagnosis following traumatic events in clinical practice, aligning with the findings of previous studies [65-67].

Vital pulp therapy

Vital pulp therapy involves treatments aimed at preserving pulp vitality and allowing for continued tooth development in pediatric patients. Despite the current methods proposed for performing vital pulp therapy, recent studies have suggested the use of lasers in this treatment approach [68, 69]. In other words, lasers have significant potential in vital pulp therapy procedures as they can disinfect the area and create a coagulative necrosis zone that, in addition to achieving hemostasis, acts as a barrier to protect the pulp from direct contact with pulp capping agents. Nevertheless, it is vital to remember that if the depth of the necrotic layer formed is excessive, the pulp healing process may be delayed. Therefore, the intensity of the laser radiation during these procedures should be carefully controlled [68].

Direct pulp capping is one of the vital pulp therapy procedures that benefit significantly from the effects of dental lasers. In fact, researchers have stated that by appropriately adjusting the irradiation technique, wavelength, and distance between the irradiated surface and the laser tip, faster hemostasis, better sterilization, and enhanced stimulation of inflammatory cells for dentin bridge formation can be achieved in direct pulp capping procedures using lasers [70]. Additionally, a variety of lasers, including diode lasers, Er: YAG, and CO₂ lasers, have been proposed for this treatment [71-73].

In a study by Yazdanfar *et al.* [71], it was observed that using a diode laser (wavelength: 808 nm, power: 1.5 W, continuous wave mode) with a 400 µm fiber diameter in direct contact with the tissue, along with resin-based tricalcium silicate paste, in direct pulp capping of 20 vital anterior and posterior teeth, resulted in the formation of a thicker dentin bridge compared to using only the resin-based tricalcium silicate paste. However, there was no significant radiographic difference between the groups after 6 months [71].

On the other hand, the study by Wang *et al.* [72], which investigated the effect of Er: YAG laser with a frequency of 10 Hz and energy of 50 mJ in combination with calcium hydroxide paste, compared to the use of calcium hydroxide paste alone in direct pulp capping of 22 vital teeth, showed significantly better treatment results after 12 months [72].

Similar positive results were observed in the study by Suzuki *et al.* [73], which examined the effect of CO₂ laser irradiation (power: 0.5 W, exposure time: 15 sec with repetition, applied energy: 3.75 J) in combination with calcium

hydroxide paste, compared to the gold standard method of using calcium hydroxide paste alone for direct pulp capping of 28 vital third molars. After 12 months, the dentinal bridge formation was notably better in the laser group. However, in this study, it was noted that dentin bridge formation, unlike the two previous laser groups, occurred with a delay and did not take place until 7 months after treatment. This finding can be related to the type of laser being applied in the study [73]. Based on the outcomes of these three studies, it can be concluded that the diode laser, due to its higher effectiveness in disinfecting dentin and achieving hemostasis, is significantly more effective than Er: YAG and CO₂ lasers in direct pulp capping treatments [71-73].

In addition to the effect of diode lasers on direct pulp capping, their impact on pulpotomy treatment in primary teeth was also observed in a recent study. In this study, a diode laser with an output power of 3 W, a power density of 5 W/cm², an energy of 4 J, an energy density of 6.7 J/cm², a frequency range of 1-50 kHz, and a 200 µm tip diameter was applied continuously for 40 sec at a distance of 2 mm from pulp tissue contact. Its effects were compared with a control group that used formocresol for hemostasis for 5 min. The results of the study indicated that clinically, there was no difference between the two methods after 9 months, and further studies are required to evaluate the precise effects of laser in pulpotomy treatments [74].

Access cavity preparation

Achieving an appropriate access cavity is critical in stepwise endodontic treatments, as it plays a significant role in the proper preparation, irrigation, and filling of the root canal. Consequently, the use of minimally invasive techniques, such as dental lasers, for preparing access cavities is advantageous in minimizing the loss of dental structure [75]. While older studies have highlighted the use of Er: YAG and Er, Cr: YSGG lasers for access cavity preparation, recent research has pointed towards the utilization of CO₂ lasers [75, 76]. For instance, in a study conducted by Simon and colleagues [76], a CO₂ laser operating at a frequency of 100 Hz was employed for dentin cutting, while a frequency of 200 Hz was used for enamel cutting on 20 developed posterior teeth, with results examined through CBCT imaging. The findings indicated that all 20 teeth were successfully accessed without any iatrogenic complications, such as gouging or perforation. Ultimately, this study advocates for the future application of CO₂ lasers in conjunction with CBCT imaging for access cavity preparation [76].

Regenerative endodontic treatments

Regenerative treatments represent a sophisticated approach to the management of immature necrotic teeth characterized by an open root apex, facilitating the ongoing development of the root structure and the eventual closure of the apex. The efficacy of these regenerative therapies is intricately linked to the successful eradication of bacteria from the root canal [53]. In a recent investigation, it was revealed that immature teeth subjected to treatment with laser-activated disinfection systems exhibited remarkable apex closure and a significant increase in root thickness following the intervention. During the initial session of this study, after meticulously rinsing the canal with a 1.5% hypochlorite solution, a pulsed diode laser, operating at a power of 1 W, was applied within the canal for 20 sec, stopping precisely 1 millimeter short of the predetermined working length. The canal was subsequently irrigated with 17% EDTA to enhance disinfection. In the subsequent session, a blood clot was deliberately induced through over-instrumentation at the terminus of the canal, upon which a collagen plug was placed, followed by the careful application of 3 to 4 millimeters of MTA [77]. The findings of this study resonate harmoniously with a systematic review conducted by Ahrari *et al.* [30]. The authors of this comprehensive review noted that while both high-power and low-power lasers possess the capability to disinfect root canals in regenerative treatments, it is solely the diode lasers that can elicit antibacterial effects akin to those achieved through the application of triple antibiotic paste. As a result, this study refrains from endorsing the utilization of lasers in regenerative treatments, instead underscoring the necessity of adhering to established gold-standard methodologies [30].

Root canals retreatment

The complete removal of gutta-percha and sealer is a crucial step in the retreatment of root canals, as it facilitates the healing of the periapical area. In essence, any residual filling materials adhering to the walls of the root canal may harbor microorganisms, potentially leading to the failure of the retreatment. Consequently, a variety of techniques have been proposed for the effective removal of root canal-filling materials, including the use of solvents, hand instruments, ultrasonic devices, nickel-titanium rotary systems, and lasers, each of which has been the subject of various discussions regarding their efficacy [78, 79].

For this aim, a study conducted by Yang *et al.* [80] examined and compared the effectiveness of different methods for the removal of sealer based on tricalcium silicate and gutta-percha during root canal retreatment. In this research, 36 single-rooted

teeth underwent root canal treatment followed by retreatment and were subsequently divided into three groups for final canal irrigation. In the first group, the canal was irrigated with 3 milliliters of 2.5% NaOCl and 3 milliliters of 17% EDTA, each for 40 sec using a 30-gauge needle. The second group received 5 sec of irrigation with 3 milliliters of 2.5% NaOCl, followed by 5 sec of activation using a non-cutting ultrasonic tip of type K, size 15, at 30% power, with four repetitions of activation. Afterward, 3 milliliters of 17% EDTA were introduced into the root canals using the same method for 40 sec. In the third group, the canals were rinsed with 3 milliliters of 17% EDTA and 3 milliliters of 2.5% NaOCl, followed by activation with an Er: YAG laser using a 300-micrometer fiber tip, delivering energy of 20 millijoules, an average power of 0.3 W, a frequency of 15 Hz, and a pulse duration of 50 microsec. The authors of the study reported that remnants of gutta-percha and sealer were observed in all groups following the final irrigation; however, the quantity was significantly lower in the third group. Therefore, the activation of 2.5% sodium hypochlorite and 17% EDTA using the PIPS method is recommended for the more effective removal of residual materials within the canal post-root canal retreatment [80].

Removal of fractured instruments from the canal

In the delicate realm of endodontics, the fracture of an instrument within the confines of the root canal represents a significant challenge, necessitating its removal or bypass to ensure the continuation of treatment. While traditional methodologies provide effective solutions, the rise of laser technology has unveiled an innovative approach: using lasers to melt obstructed files or liquefy the surrounding tissue, thereby facilitating the delicate task of navigating these impediments. However, evidence indicates that the use of lasers to dissolve fractured files can generate significant thermal fluctuations, which may compromise the integrity of adjacent anatomical structures. Furthermore, in the intricate labyrinth of narrow or curved root canals, the application of lasers to melt surrounding tissues poses a perilous risk of perforations. Thus, the application of lasers in such circumstances is not logical [10]. Nonetheless, a recent study highlights the potential of lasers in effectively managing fractured instruments within the canal, sparking a debate that invites further exploration and understanding [81].

In the study conducted by Namour *et al.* [81], the Nd: YAP laser, operating at a frequency of 10 Hz, with a power output of 3 W, energy of 300 millijoules, with a fiber diameter of 200 micrometers, was employed to retrieve fractured nickel-titanium files from within the canal. The results were meticulously compared across different conditions. Specifically,

the study examined five groups where the Nd: YAP laser was applied singularly for durations of 1, 3, 5, 10, and 15 sec. It was observed that the thermal variations exceeded the tolerance threshold for surrounding tissue during the 10- and 15-sec exposures. Subsequently, the Nd: YAP laser was utilized in four additional groups, employing a pulsed approach across multiple sessions. These groups received a series of three 5-sec exposures with rest periods of 30 sec, three 5-sec exposures with rest intervals of 60 sec, two 5-sec exposures with a 30-sec rest, and finally, two sessions of 5-sec exposures with just 5 sec of rest. Notably, the thermal variations that surpassed the desired limits were exclusively recorded in the last group. Overall, this study concluded that the Nd: YAP laser is capable of effectively cutting and melting nickel-titanium files without causing the melting of the surrounding dentin structures. Moreover, the most favorable thermal variations are achieved when the laser exposure is administered in three series of 5 sec with a 30-sec rest period [81].

Removal of fiber post from the canal

Since patients often request to retain their natural teeth, the removal of fiber posts from root-treated teeth when re-treatment is necessary poses a significant challenge for dentists. In fact, due to the complete bonding of fiber posts to the dentin, their extraction through mechanical or ultrasonic methods can render teeth susceptible to microcracks and dentinal fractures. Consequently, dentists frequently resort to the complete extraction of the tooth and the placement of an implant. However, the introduction of laser technology in dentistry has

revolutionized endodontics by demonstrating a positive impact on the removal of fiber posts [82].

In their laboratory investigation, Deeb *et al.* [82] discerned that the application of the Er: YAG laser in a pulsed modality with a frequency of 15 Hz, power of 3 W, and an energy of 135 millijoules for 50 microsec per pulse, enhances the efficiency of fiber post removal, achieving a speed of extraction five times greater than that of ultrasonic instruments. Moreover, this study showed that the thermal alterations instigated by the laser application were significantly less pronounced compared to those resulting from the ultrasonic technique, thereby rendering the utilization of the laser method significantly more advantageous [82].

Although the investigation by Deeb *et al.* [82] characterizes the employment of lasers as a reliable and safe method for the extraction of fiber posts, the research conducted by Zamanian *et al.* [83] brings to light the inadequacies of the Er: YAG laser in achieving complete debonding of glass fiber posts within the confines of the canal. In their study, the Er: YAG laser was utilized at a frequency of 20 Hz, with a power output of 7 W and an energy level of 350 millijoules for the removal of fiber posts. The findings revealed that not only did the laser lack efficacy in fully debonding the fiber post, but it also posed a potential risk of fracturing the post in certain cases [83]. Given the existing contradictions between the findings of these studies and the reported limitations associated with laser applications, there is a pressing need for further investigations to thoroughly examine this matter in future research [82, 83].

Table 2. Summary of the effects of dental lasers in various therapeutic procedures in endodontics

Treatment Process	Argon Laser	He-Ne Laser	Nd: YAP Laser	Erbium Lasers	CO ₂ Laser	Diode Laser	Nd: YAG Laser
Cleaning and disinfection of the root canal				✓		✓	✓
Removal of debris and smear layer				✓		✓	
Non-surgical treatment of periapical lesions				✓		✓	
Apical seal							✓
Removal of residual materials from the canal				✓			
Post-treatment pain management						✓	✓
Pulp vitality diagnosis		✓				✓	
Vital pulp therapy				✓	✓	✓	
Access cavity preparation				✓	✓		
Regenerative treatment						✓	
Root canal retreatments				✓			
Apicoectomy				✓	✓		✓
Removal of fractured instruments from the canal			✓				
Removal of fiber post from the canal				✓			
Alleviation of nausea						✓	
Sterilization of Instruments						✓	

Alleviation of nausea

Nausea emerges as a prevalent concern in dental and endodontic procedures, often intricately linked to the utilization of rubber dams or an intensified gag reflex exhibited by patients. This reflex, if left unchecked, poses a significant threat to the efficacy of the treatment. Thus, the preemptive management of the gag reflex, particularly in pediatric patients, is crucial for minimizing the likelihood of procedural complications [84]. In light of this, a novel study has proposed the application of a laser emitting power of 4 joules per centimeter, employing mechanisms akin to acupuncture, on specific acupoints associated with nausea, referred to as PC6 points. This innovative approach has demonstrated promise in diminishing the sensations of gagging. Furthermore, it has been noted that the application of laser therapy to these targeted areas can also serve as a gentle and effective method for alleviating anxiety in children undergoing dental treatment [85].

Sterilization of instruments

Sterilization is a process of entirely eradicating microorganisms and stands as a prerequisite for the successful execution of endodontic treatments. While traditional methods of sterilization in the realm of dentistry, including autoclaving, chemoclaving, and the application of dry heat, remain widely employed, the advent of modern technologies has ushered in the use of diode, CO₂, Ar, and Nd: YAG lasers as supplementary modalities for sterilization [3]. A notable study conducted by Ameer *et al.* [86] delved into [the efficacy of various sterilization techniques for hand files. This research juxtaposed the outcomes of autoclaving at a temperature of 121 degrees Celsius for 15 min, immersing files in a 2.4% glutaraldehyde solution for 12 h, and applying a diode laser at 3 W for 3 sec. The results revealed that the diode laser, hindered by its shallow depth of penetration, proved considerably less effective than the autoclaving method, failing to completely eliminate microorganisms from the instrument's surface. According to these findings, it is prudent to regard the use of lasers as an adjunctive approach to the sterilization of instruments rather than a standalone solution [86].

To sum up, a review of the results presented in various studies indicates that diode lasers and the erbium family exhibit the most significant effects, while argon lasers demonstrate the least impact in different therapeutic procedures within the field of endodontics. A summary of the applications of various lasers in endodontics can be found in [Table 2](#).

Based on the present review, several limitations must be acknowledged. The study's exclusive reliance on published literature from selected databases (PubMed, Google Scholar,

Embase, Scopus) between 2015 and 2024 may introduce publication bias and overlook relevant studies outside this timeframe or in other sources. The inclusion of only English-language articles further restricts the global applicability of the findings. Additionally, the heterogeneity in laser parameters, methodologies, and outcome measures across the 86 included studies limits the ability to perform a quantitative meta-analysis or draw uniform conclusions regarding efficacy. The predominance of *in vitro* and *ex vivo* studies over clinical trials also constrains the direct translation of results to clinical practice. Finally, the lack of standardized protocols for laser application in endodontics underscores the need for more rigorous, homogeneous, and clinically oriented research to validate these preliminary findings.

Conclusion

The integration of dental lasers into endodontic practice represents a noteworthy technological advancement that offers promising benefits such as enhanced disinfection, improved hemostasis, and potential reductions in postoperative discomfort. However, the current body of evidence remains largely heterogeneous, with the majority of studies being *in vitro* or *ex vivo* in design. Although preliminary findings suggest that diode and erbium lasers, in particular, hold potential as adjunctive tools in various endodontic procedures, the scarcity of robust clinical trials limits definitive conclusions regarding their clinical efficacy and long-term safety. Therefore, while dental lasers may serve as valuable supplementary instruments in selected endodontic applications, further well-designed, large-scale clinical studies are essential to establish standardized protocols and confirm their true clinical utility.

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