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REVIEW

Er:YAG laser in oral medicine: mechanisms, efficacy, and future perspectives

Shaorong Li[1,2,§], Jiaqi An[1,§], Yongkang Li[1], and Chen Zhang[1] ✉

[1] *Department of Operative Dentistry and Endodontics, Beijing Stomatological Hospital, Capital Medical University, Beijing, 100070, China*
[2] *Laboratory of Oral Health and Homeostatic Medicine, School of Stomatology and Beijing Laboratory of Oral Health, Capital Medical University, Beijing, 100070, China*
[§] *These authors contributed equally to this work.*

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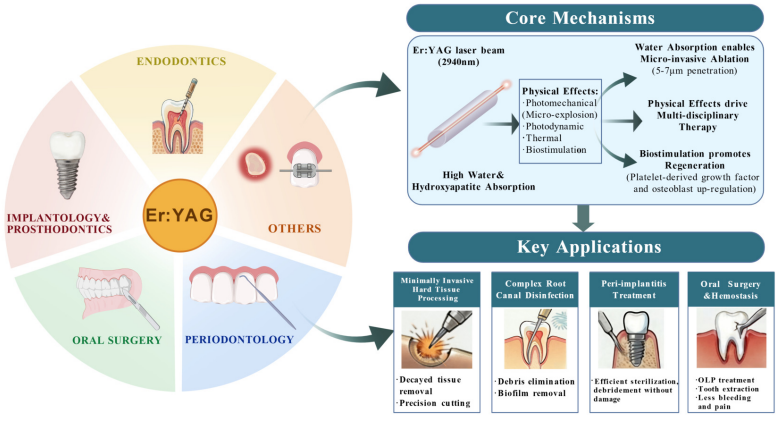
ABSTRACT: The erbium-doped yttrium aluminum garnet (Er:YAG) laser, characterized by high water absorption, precise ablation, antibacterial effects, and biostimulatory functions, represents a transformative technology in oral medicine. This review explores its diverse applications. In endodontics, it is used for caries removal, cavity preparation, hypersensitivity management, vital pulp therapy, and root canal treatment, offering reduced pain and improved adhesive performance. In periodontology, it facilitates debridement and tissue regeneration through both nonsurgical and surgical interventions. In implantology and prosthodontics, the Er:YAG laser provides novel strategies for peri-implantitis management, bone defect conditioning, and surface modification. In oral and maxillofacial surgery, it is applied in soft tissue resection, osseous surgery, and the management of medication-related osteonecrosis, ensuring precise ablation and faster recovery. Furthermore, it shows promise in orthodontics and pain management. Despite challenges, such as insufficient parameter standardization and the need for long-term evidence, future developments, including evidence-based guidelines and integration with artificial intelligence and real-time imaging, are expected to synergize with regenerative medicine. These advances will propel the Er:YAG laser toward increasingly precise, minimally invasive, and personalized dental diagnosis and treatment across clinical subspecialties.



KEYWORDS: Er:YAG laser, oral medicine, endodontics, periodontology, pain control

1 Introduction and mechanism

With continuous improvements in living standards, both clinicians and patients increasingly seek efficient, comfortable, precise, and minimally invasive surgical approaches to achieve durable and stable therapeutic outcomes[1-4]. Erbium lasers, primarily the erbium-doped yttrium aluminum garnet (Er:YAG) laser with a wavelength of 2940 nm and the erbium, chromium-doped yttrium scandium gallium garnet (Er,Cr:YSGG) laser with a wavelength of 2780 nm, have emerged as important tools in the prevention and treatment of oral diseases[5-8]. Following approval by the United States Food and Drug Administration in 1997 and 1998 for dental hard tissue preparation and the treatment of oral soft and hard tissues, respectively, erbium lasers gradually became a pivotal technology for overcoming the limitations of conventional therapies because of their unique physicochemical properties[9]. Cutting-edge technological advances and ongoing scientific research have steadily expanded the indications of this class of lasers[10]. The core advantage of these lasers stems from the high absorption of their wavelengths by water, a primary component of oral tissues, and by hydroxyapatite (HAP), the main constituent of dental hard tissues. This property enables precise tissue ablation or structural modification through a "micro-explosion" mechanism. Notably, the Er:YAG laser exhibits a penetration depth of only 5–7 μm in enamel and dentin, significantly reducing the risk of thermal damage to adjacent tissues[11-13].

Consequently, the unique physical properties of the Er:YAG laser elevate it beyond a single-purpose instrument to a versatile, cross-disciplinary platform technology. Its core capability—selective, minimally invasive ablation based on tissue water content—provides a unified technical pathway for a central tenet of oral

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✉Address correspondence to Chen Zhang, endozhangchen@163.com

medicine: the precise removal of pathological tissue while maximally preserving healthy structure and creating a favorable environment for regeneration. This shared principle underpins its diverse applications across endodontics, periodontology, implantology, and surgery. The following sections detail its advances within individual specialties and culminate in a discussion of its potential to facilitate the integration of multidisciplinary treatment strategies.

Although previous reviews have addressed the mechanisms and clinical utility of the Er:YAG laser, they have typically focused on individual diseases or specific subdisciplines, whereas comprehensive reviews encompassing the full scope of oral medicine remain relatively scarce[14-18]. This article reviews the clinical applications of the Er:YAG laser in oral medicine and aims to provide insights into its use in clinical diagnosis and treatment.

2 Application in oral medicine

In clinical dentistry, the application value of the Er:YAG laser spans multiple specialized fields, including endodontics, periodontology, implantology and prosthodontics, as well as oral surgery.

2.1 Application in endodontics

Endodontics is primarily concerned with the diagnosis and management of conditions such as dental caries, dentin hypersensitivity (DH), and pulp diseases. The therapeutic objective has evolved from simple "lesion removal" to a philosophy centered on "minimally invasive preservation and functional regeneration"[19,20]. Conventional therapeutic techniques, including mechanical caries removal, chemical desensitization, and mechanical root canal preparation, are often limited by excessive loss of tooth structure, inconsistent long-term efficacy, and an elevated risk of pulp irritation[21-24]. By leveraging its high selectivity for water and HAP, the Er:YAG laser enables precise tissue interaction through photothermal and photomechanical effects, thereby offering a novel strategy for minimally invasive interventions in operative dentistry and endodontics[25,26]. The following sections systematically describe the current applications, research progress, and clinical value of the Er:YAG laser in areas including caries management and remineralization, DH treatment and sealing effects, tooth whitening, vital pulp therapy (VPT), as well as root canal treatment (RCT) and apical surgery.

2.1.1 Dental caries

Dental caries is a chronic, progressive disease characterized by the destruction of dental hard tissues under the influence of multiple factors, primarily bacteria[27]. The World Health Organization (WHO) ranks dental caries as the third most prevalent disease affecting human health, following cardiovascular diseases and cancer. According to the WHO's Global Oral Health Status Report published in 2022, nearly 3.5 billion people worldwide suffer from oral diseases, with permanent tooth caries representing the most common condition[28]. This condition has emerged as a significant global public health challenge[29].

Current caries management primarily relies on a "caries removal and restoration" approach, whereas remineralization therapy is mainly employed for early enamel caries[30,31]. Traditional techniques present notable limitations. The diagnosis of early-stage lesions is constrained because conventional visual–tactile examination often fails to detect subsurface enamel demineralization, thereby delaying timely remineralization and allowing lesion progression to cavitation[32-34]. Mechanical caries removal—an invasive procedure that relies on high-speed handpieces or manual excavators to eliminate softened carious tissue—lacks the precision to reliably differentiate between "infected dentin" and "demineralized dentin," often resulting in excessive removal of sound tooth structure[35,36]. Furthermore, the vibration and noise associated with high-speed handpieces can induce dental anxiety, particularly in pediatric patients[37].

In contrast, the Er:YAG laser offers distinct advantages in precision and tissue preservation during caries removal[14,38]. Its core mechanism involves the preferential absorption of the 2940 nm wavelength by water within the carious lesion, generating micro-explosions that selectively ablate demineralized dentin or enamel. In contrast, sound tissue—characterized by higher mineral content and lower water content—absorbs less laser energy and therefore remains largely intact. Studies conducted by multiple research groups, despite variations in parameters, have consistently demonstrated its superior tissue-preserving capability compared with traditional mechanical removal[39-41].

A retrospective study by Feng[25] demonstrated that enamel irradiated with an Er:YAG laser maintained higher surface microhardness, shallower lesion depth, and less mineral loss in an acidic environment, indicating its potential for enamel protection. Moreover, research by Allam[42] indicated that the combination of the Er:YAG laser and fluoride application was more effective in inhibiting enamel demineralization than the laser alone. In contrast, a retrospective study by Tao[43] found that cavity preparation using the Er:YAG laser required more time than conventional methods. However, the laser reduced the need for local anesthesia. No significant differences were observed between the two techniques with respect to restoration failure rates, pulp vitality, or postoperative sensitivity. Milc[44] also reported that cavity preparation with the Er:YAG laser required, on average, 2.5 times more time than preparation with a conventional dental turbine. Their study further confirmed the efficacy of the Er:YAG laser for hard tissue preparation in primary teeth, with enamel preparation performed using 230 mJ pulse energy and dentin preparation using 120 mJ and 150 mJ pulse energy. Optimal operating frequencies were 10 Hz and 20 Hz. Patient discomfort, measured using a visual analog scale (VAS), was rated as 0, significantly enhancing overall comfort and effectively alleviating the anxiety and discomfort commonly associated with dental treatment in children, thereby improving treatment acceptance. Furthermore, Krmek[45] demonstrated that the Er:YAG laser enables selective caries removal, with a maximum pulp chamber temperature increase of only 1.99°C, which is substantially lower than the increase of 20°C or more associated with conventional turbines, indicating greater safety. Wang[46] investigated the effects of the Er:YAG laser at different output energy levels on the biological behavior of human dental pulp cells (hDPCs). The results suggested that irradiation at 100 mJ may be suitable for deep caries removal because it did not adversely affect the biological behavior of hDPCs. These *in vitro* findings indicate that Er:YAG laser caries removal results in a significantly lower pulp chamber temperature increase compared with conventional dental turbines and that irradiation at specific energy levels (e.g., 100 mJ) does not adversely affect the biological behavior of cultured hDPCs. Moreover, Lin[47] systematically evaluated the effect of Er:YAG laser dentin pretreatment on the shear bond strength (SBS) of composite resin. The findings

indicated that, when used alone, the Er:YAG laser achieved bond strength comparable to that of conventional mechanical preparation, although this conclusion is limited by high heterogeneity and the *in vitro* study design.

In summary, the Er:YAG laser shows potential for the management of dental caries; however, additional *in vitro* and clinical studies are required to determine whether its irradiation can effectively prevent enamel caries in clinical settings[48]. The core advantages of caries removal with the Er:YAG laser include the absence of vibration, minimal noise, and limited thermal side effects, making it more acceptable for children and adults with dental phobia. Furthermore, its wide range of adjustable pulse widths enables high cutting precision, rendering it suitable for precise hard tissue interventions[49]. In addition, the safety of the laser in caries removal has been validated. Although animal studies have suggested a potential temperature increase in the pulp, clinical studies have shown no significant difference in pulp vitality[50]. However, a recognized disadvantage is its relatively lower efficiency, as most studies report significantly longer operating times compared with conventional drills, which warrants further investigation.

2.1.2 DH

DH is characterized by short, sharp pain arising from exposed dentin in response to external stimuli, typically thermal, evaporative, tactile, osmotic, or chemical in nature[51,52]. The hydrodynamic theory is widely accepted to explain its mechanism; external stimuli induce fluid movement within the dentinal tubules, which activates pulpal nerves and leads to pain[53,54]. DH can significantly affect patients' daily activities, such as eating and brushing, thereby reducing oral health–related quality of life[55]. A cross-sectional study by Favaro[56] reported significant heterogeneity in DH prevalence, with a best-estimate prevalence of 11.5%. The average prevalence across all included studies was 33.5%, and subject type, age range, recruitment strategy, and number of study sites were identified as significant contributors to prevalence heterogeneity.

Current DH management strategies primarily focus on sealing dentinal tubules or reducing nerve excitability. Traditional techniques, such as topical desensitizing agents or restorative procedures, often present limitations, including transient effectiveness and procedural complexity[57,58]. In contrast, lasers can achieve dentinal tubule sealing through a "melting–recrystallization" mechanism. Laser energy is absorbed by water on the dentin surface, generating localized high temperatures (800–1000°C) that cause superficial dentin (1–2 μm) to melt. Upon cooling, a glass-like sealing layer forms, and the tubule orifices become narrowed or occluded by the resolidified material. Additionally, the thermal effect of the laser can denature surface proteins, further enhancing the stability of the seal[59,60]. Laser therapy provides both immediate analgesic effects, reflected by a reduction of ≥3 points on the VAS after treatment, and sustained efficacy over 6–18 months of follow-up[15]. Notably, the Er:YAG laser has a water absorption coefficient approximately 15 times higher than that of the carbon dioxide (CO_2) laser and 20,000 times higher than that of the neodymium-doped yttrium aluminum garnet (Nd:YAG) laser, allowing efficient tubule sealing with minimal thermal effects[13].

Moreover, Zhuang[61] demonstrated that Er:YAG laser irradiation at 0.5 W (167 J/cm^2) was highly effective in sealing dentinal tubules, resulting in a significantly lower percentage of open tubules compared with other groups, with no significant morphological changes observed in the pulp or odontoblasts after irradiation. Belal[59] found that both the CO_2 and Er:YAG lasers were effective in treating DH and significantly increased tubule sealing rates, with the Er:YAG laser demonstrating superior efficacy. Neither laser altered the mineral composition of dentin. Aranha[62] reported that both Er:YAG and Er,Cr:YSGG lasers effectively reduced DH without impairing pulp vitality. Although their performance varied depending on the type of stimulus, the Er:YAG laser provided the most durable relief from air-blast stimulation.

In summary, multiple studies confirm that the Er:YAG laser effectively seals dentinal tubules through a thermal melting mechanism, representing an efficient treatment modality for DH. Its core advantages include high sealing rates, minimal thermal effects, long-term stability, and procedural simplicity. Research discrepancies primarily concern whether lasers should be combined with adjunctive techniques. Some researchers have suggested that combining lasers with agents such as NovaMin (bioactive glass) can further increase the sealing rate (exceeding 95%) but at additional cost, whereas laser monotherapy is considered sufficient for most clinical needs and more cost-effective[60]. However, it is important to note that no laser can completely eliminate DH pain. Clinical management should therefore be complemented by oral hygiene instruction and other supportive measures. Future research should explore the synergistic sealing mechanisms of lasers combined with bioactive materials to prolong therapeutic efficacy[63].

2.1.3 Tooth discoloration and bleaching

Tooth discoloration refers to abnormal tooth coloration resulting from extrinsic factors (e.g., coffee, tobacco, or tea) or intrinsic factors (e.g., tetracycline staining, dental fluorosis, or pulpal necrosis)[64-67]. With increasing aesthetic demands, tooth bleaching has become a common therapeutic strategy. Current bleaching techniques primarily rely on chemical agents, such as hydrogen peroxide (H_2O_2)–based bleaching gels, and adjunctive physical activation methods, which are associated with limitations, including pulp irritation and enamel surface alterations[68,69]. The application of the Er:YAG laser offers a potential approach for achieving efficient bleaching with reduced adverse effects. The 2940 nm wavelength of the Er:YAG laser is readily absorbed by the bleaching gel, which typically contains 40%–65% water, thereby accelerating H_2O_2 decomposition and shortening treatment duration. Previous studies have substantiated the safety of this approach[70-72].

Cai[73] demonstrated a significant correlation between Er:YAG laser energy and bleaching efficacy. Energy levels of ≥60 mJ significantly enhanced the bleaching effect of 37% H_2O_2, whereas 80–100 mJ showed a marginal, statistically nonsignificant improvement. However, Awati[72] reported that the potassium titanyl phosphate (KTP) laser outperformed Nd:YAG, Er:YAG, and diode lasers in tooth bleaching and was associated with the lowest pulpal temperature increase, thereby reducing the risk of irreversible pulpal damage. Research by Ergin[74] indicated that three different photoactivation systems—the Er:YAG laser, diode laser, and light-emitting diode—all achieved effective tooth bleaching, with no significant difference in color change among them. Notably, the Er:YAG laser group exhibited the highest enamel SBS after bleaching, suggesting a potential advantage for subsequent adhesive procedures.

These seemingly inconsistent findings likely stem from differences in the physical properties of the laser systems and their

interaction mechanisms with bleaching gels and dental tissues. Wavelength and absorption characteristics: The Er:YAG laser (2940 nm) is highly absorbed by water molecules. When applied to water-rich (40%–65%) bleaching gels, its energy is rapidly absorbed and converted into heat, thereby accelerating H_2O_2 decomposition and enhancing the bleaching effect[73–74]. The energy-dependent effect observed by Cai et al. aligns with this mechanism[73]. Comparison among laser systems: The reportedly superior performance of the KTP laser (532 nm), as noted by Awati et al.[72], may be attributed to its wavelength more closely matching the absorption peak of certain photosensitive components within the bleaching gel, thereby inducing a more efficient photochemical reaction. The lower pulpal temperature increase associated with the KTP laser further suggests that its energy delivery and tissue interaction pattern differ from the water-targeted mechanism of the Er:YAG laser. Study design and outcome measures: The finding by Ergin et al. that various photoactivation systems, including the Er:YAG laser, showed no significant difference in bleaching efficacy[74]may be related to study-specific endpoints (e.g., bleaching duration and color measurement protocols) or to the particular bleaching gel formulation used. These factors may offset the inherent mechanistic differences between laser systems. Therefore, evaluating the superiority of laser-assisted bleaching should not be separated from the specific laser–gel combination and study parameters. Future comparative studies should strictly control variables such as bleaching gel composition, irradiation energy density, and clinical protocols.

In summary, the Er:YAG laser provides a minimally invasive approach to tooth bleaching, effectively achieving whitening while reducing the risks of pulp irritation and enamel damage[75]. However, current research predominantly focuses on short-term outcomes, and long-term data on the rate of pigment re-deposition remain insufficient. Furthermore, its efficacy in managing severe intrinsic discoloration remains limited. Future investigations should aim to optimize bleaching gel formulations in conjunction with laser parameters to further expand its clinical applicability.

2.1.4 VPT

VPT encompasses a range of procedures aimed at preserving pulp vitality and function, including selective caries removal, DPC, indirect pulp capping, and pulpotomy. It is primarily indicated for carious pulp exposure (with an exposure diameter <1 mm), mechanical pulp exposure, or early-stage pulpitis in immature permanent teeth. The core objective is to promote pulp healing and the formation of reparative dentin[76-78]. Systematic research conducted in the 1940s–1950s indicated that the success rate of DPC was only 60%–70%, which was significantly lower than the 80%–90% success rate of RCT[76]. Over the past two decades, advances in biomaterials, refinements in technique, and an improved understanding of pulp repair mechanisms have propelled the development of VPT[79,80]. Conventional vital pulp preservation techniques are often associated with challenges, including low healing rates and a high risk of pulp irritation[81,82]. The antibacterial, hemostatic, and biostimulatory effects of the Er:YAG laser offer a novel approach to potentially enhance treatment success.

2.1.4.1 DPC

In studies focusing on DPC for cariously exposed permanent teeth, the Er:YAG laser enables selective removal of carious tissue, which has a higher water content, thereby reducing bacterial load on the pulp surface and lowering the risk of infection. Simultaneously, it coagulates superficial pulp tissue to achieve rapid hemostasis. Furthermore, the laser can effectively remove the smear layer, open dentinal tubules, and facilitate closer adaptation of the pulp-capping material, thereby reducing microleakage[83,84]. Jasrasaria[85] demonstrated that the combined application of the Er:YAG laser and Biodentine significantly improved both clinical and radiographic success rates compared with Biodentine alone or the Er:YAG laser alone. The combined protocol showed pronounced advantages in promoting dentin bridge formation and reducing postoperative sensitivity, offering a minimally invasive and effective strategy for VPT in mature permanent teeth and further strengthening the evidence base for Er:YAG laser application in vital pulp preservation. Conversely, Kermanshah[86] found no statistically significant difference in the clinical success rate of DPC between ProRoot MTA alone and its combination with the Er:YAG laser. In contrast, Wang[87] reported that in DPC for cariously exposed permanent teeth, the 12-month cumulative success rate with Er:YAG laser-assisted treatment (91.7%) was significantly higher than that of conventional calcium hydroxide treatment (68.2%). The distinctive results observed across these studies are mainly attributable to differences in the laser parameters used. Overall, the laser-assisted method has been noted for its procedural simplicity and fewer side effects, suggesting that it may represent a favorable clinical option.

However, current clinical evidence regarding Er:YAG laser-assisted DPC remains inconsistent, largely because of a lack of standardization across several key dimensions. These discrepancies may be attributed to variations in the following aspects: laser parameters, as inconsistent settings for energy, frequency, pulse mode, and irradiation time directly influence the thermal and biostimulatory effects on pulp tissue; the use of different capping materials across studies, as the laser-modified dentin surface may interact differently with each material's biocompatibility and sealing properties; variations in critical prognostic factors, such as exposure size, hemorrhage control, and preoperative pulp inflammation status, which significantly affect outcomes; and differences in the definitions of clinical or radiographic success and in follow-up duration, which can lead to divergent interpretations of treatment success. Therefore, extrapolating the existing preliminary evidence to broad clinical conclusions requires considerable caution.

2.1.4.2 Pulpotomy

For early-stage pulpitis, the Er:YAG laser can serve as an alternative to mechanical pulpotomy, enabling precise and minimally invasive amputation of pulp tissue[88]. *In vitro* and animal studies suggest that Er:YAG laser irradiation may stimulate pulp cells to secrete type I collagen and upregulate factors associated with alkaline phosphatase activity and dentin bridge formation. However, whether these potential biostimulatory effects can be consistently translated into superior healing outcomes in clinical settings requires validation through prospective clinical studies[89-93]. Wang[94], in a study applying Er:YAG laser pulpotomy to asymptomatic, deeply carious primary teeth in children, found that although the time required for pulp tissue amputation was significantly longer than that with conventional methods, the hemostasis time and total treatment time were significantly shorter. However, Jamali[95] reported that during a 3–18 month follow-up period, there was no statistically significant difference in clinical and radiographic success rates between various laser pulpotomy techniques and formocresol pulpotomy for primary molars. Among the evaluated laser systems,

the diode laser was considered more suitable for primary tooth pulpotomy.

The Er:YAG laser represents a promising technical adjunct in VPT. Its theoretical advantages include precise caries removal, effective hemostasis, and potential surface disinfection. Preliminary clinical studies suggest that, under certain conditions—such as when combined with specific bioactive materials—laser-assisted protocols may achieve success rates comparable to or higher than those of conventional methods[11,90]. However, conflicting study results indicate that its efficacy is inconsistent and appears to be highly dependent on the technical, material, and case-related variables discussed above[89]. Currently, large-scale, long-term randomized controlled trials with strictly controlled variables are lacking to confirm its definitive added value. Therefore, although the Er:YAG laser is a promising tool, it has not yet been established as a standard or preferred option in VPT. Future research should focus on standardizing laser application protocols and rigorously validating its efficacy within well-defined clinical settings.

2.1.5 RCT and apical surgery

RCT, comprising root canal preparation, cleaning and disinfection, and obturation, serves as the cornerstone for managing pulpal necrosis and apical periodontitis[96,97]. Apical surgery is employed following RCT failure and involves procedures such as apicoectomy, apical retro-preparation, and retro-obturation[98,99]. Traditional techniques face limitations in effectively cleaning complex root canal anatomies and achieving precise apicoectomy[100,101]. The Er:YAG laser, owing to its precise tissue interaction properties, demonstrates significant advantages in root canal disinfection, canal cleaning, and apical surgery[102,103].

2.1.5.1 RCT

Mechanical preparation during conventional RCT often fails to completely clean anatomically complex areas of the root canal system, and accumulated dentin debris and the smear layer remain on the canal walls. This smear layer has been shown to impede the penetration of irrigants and sealers into dentinal tubules, thereby hindering adequate cleaning and sealing[104,105]. Consequently, chemical disinfection through irrigation is essential. Conventional needle irrigation (CNI) is commonly used; however, irrigant flow is limited to approximately 2 mm short of the apical foramen[106,107], which compromises its efficacy and may lead to the persistence of biofilms and viable microbial flora in the apical region[108].

In RCT, the Er:YAG laser is primarily applied for laser-activated irrigation (LAI) to remove the smear layer and enhance disinfection. The core mechanism involves the generation of strong acoustic streaming and cavitation through photoacoustic phenomena, thereby significantly improving irrigant dynamics. As illustrated in Figure 1, this approach induces potent acoustic streaming and cavitation, which enhances irrigant hydrodynamics throughout the root canal system and facilitates penetration into anatomically complex and otherwise inaccessible regions. Two primary modalities are photon-induced photoacoustic streaming (PIPS) and shock wave-enhanced emission photoacoustic streaming (SWEEPS), in which PIPS relies on single-pulse Er:YAG laser-induced photoacoustic cavitation, whereas SWEEPS uses a dual-pulse emission mode to amplify bubble collapse and shock wave generation within the irrigant[109]. Mahmoud[110] evaluated smear layer removal efficiency using scanning electron microscopy (SEM) and found that Er:YAG laser treatment followed by ethylenediaminetetraacetic acid (EDTA) irrigation resulted in the highest level of cleanliness compared with sodium hypochlorite (NaOCl) irrigation combined with EDTA, phthalocyanine (Pc)-activated photodynamic therapy (PDT), and bioactive glass nanoparticle treatment. Furthermore, Bao[111] showed that Er:YAG LAI techniques (PIPS and SWEEPS) and sonic irrigation (EDDY) were significantly superior to CNI and passive ultrasonic irrigation (PUI) in biofilm removal and bactericidal effects in hard-to-reach areas. SWEEPS demonstrated the greatest efficacy in biofilm removal within apical grooves, whereas SWEEPS and EDDY were most effective in bacterial elimination within dentinal tubules. Uslu[112] reported that PIPS and SWEEPS achieved optimal smear layer removal across all root canal regions, particularly in the apical third. PIPS yielded the greatest tubular penetration depth and percentage, facilitating closer adaptation of sealers to dentin. Moreover, Liu[113] found that PIPS significantly outperformed ultrasonically activated irrigation (UAI) and CNI in removing debris and the smear layer from the apical region.

2.1.5.2 Apical surgery

In apical surgery, the Er:YAG laser is used for apicoectomy and apical retro-preparation, offering advantages such as precise cutting and reduced tissue trauma. Operating in a "photomechanical ablation" mode with air–water spray cooling, it minimizes thermal damage and avoids carbonization. Additionally, it may promote bone healing through biostimulatory effects, such as stimulating platelet-derived growth factor secretion and activating osteoblast proliferation[9,114].

Lietzau[9] demonstrated that Er:YAG laser-assisted apicoectomy performed under a surgical microscope resulted in significantly better postoperative inflammation control and healing outcomes compared with conventional surgery, suggesting that it may

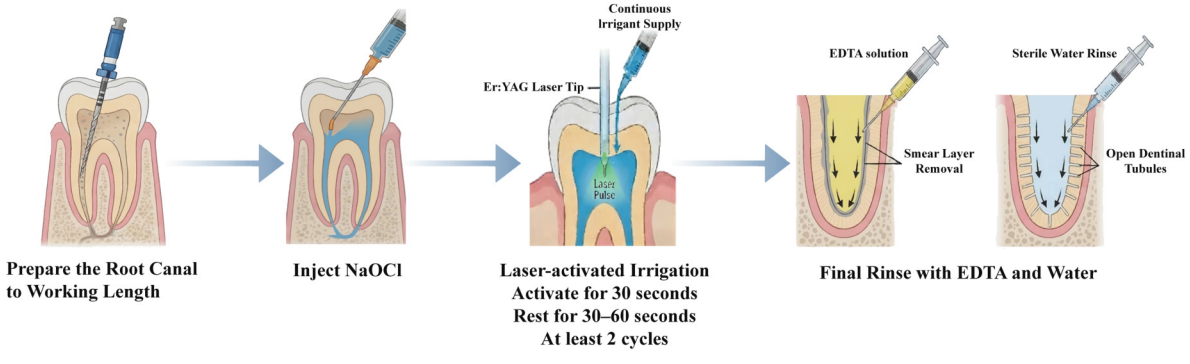

Figure 1 The schematic illustrates application of Er:YAG laser in root canal activation & irrigation.

represent a favorable option. However, prospective studies are needed to isolate the respective effects of the laser and the surgical microscope. A limitation of conventional Er:YAG lasers is that prolonged pulse tails may cause tissue desiccation and carbonization. Variable square pulse (VSP) technology optimizes pulse shape to address this limitation. Grgurević[115] concluded that the VSP Er:YAG laser can be safely used for apicoectomy with acceptable therapeutic outcomes and identified high energy and frequency settings as key factors for enhancing procedural efficiency.

A consensus across studies is that the Er:YAG laser, via SWEEPS or PIPS technologies, enhances cleaning efficacy in complex root canal systems and improves the quality of apical surgery, offering advantages over conventional techniques. Discrepancies in the literature primarily concern optimal application parameters: SWEEPS is often preferred for cleaning curved canals, whereas higher power settings are recommended for cutting during apical surgery. Consequently, the Er:YAG laser provides a minimally invasive and precise approach to RCT and apical surgery, markedly improving treatment quality, particularly in complex canal cleaning and apicoectomy precision. However, most current evidence is derived from *in vitro* studies. The influence of clinical variables, such as anatomical variations in root canal systems, on laser efficacy requires validation through well-designed *in vivo* studies. Furthermore, the substantial initial investment required for laser equipment currently limits its routine adoption in general dental practice.

The application value of the Er:YAG laser in endodontics is supported by substantial evidence. Its minimally invasive nature, superior patient comfort, and efficacy as an adjunctive irrigation modality during RCT are well established, solidifying its role in selective caries removal and biofilm management. Therapeutic benefits in dentinal hypersensitivity and apical surgery have also been validated; however, optimal protocols, such as potential combinations with other agents, require further refinement. In contrast, its ability to significantly improve long-term success rates in VPT remains controversial because of insufficient high-level evidence. Similarly, proposed effects such as caries prevention and biological stimulation of pulp repair are primarily supported by preliminary studies and therefore remain speculative. Despite these potential advantages, the widespread adoption of the Er:YAG laser in routine endodontic practice faces several challenges. The initial acquisition and ongoing maintenance costs are considerably higher than those of conventional dental turbines and ultrasonic units. Its operation requires specialized training and involves a learning curve, as inappropriate parameter settings may compromise procedural efficiency or increase the risk of inadvertent tissue damage. Furthermore, the relatively large handpiece size may limit maneuverability in areas with restricted visual access, such as posterior regions. Consequently, its current application may be best suited to selected cases in which minimally invasive treatment and enhanced comfort are paramount (e.g., pediatric or anxious patients) or as a valuable adjunct to conventional techniques. Overall, the Er:YAG laser serves as a precise and minimally invasive adjunctive tool, and its broader clinical integration will depend on standardized parameters and robust long-term clinical studies.

2.2 Periodontology

Periodontology focuses on the diagnosis and treatment of diseases affecting the periodontal supporting tissues, primarily gingivitis and periodontitis. The pathogenesis involves an inflammatory host immune response triggered by dysbiosis of the oral microbiota. If left untreated, this process can result in progressive alveolar bone resorption, tooth mobility, and eventual tooth loss, making periodontitis the leading cause of tooth loss in adults[116-118]. Epidemiological data show that there were 1.1 billion prevalent cases of severe periodontitis worldwide in 2019, and the global age-standardized prevalence rate increased by 8.44% between 1990 and 2019.[119]. Conventional periodontal therapies, including scaling and root planing (SRP) and periodontal surgery, often fail to completely eliminate pathogenic bacteria that have invaded periodontal tissues, and achieving optimal wound healing remains challenging. Therefore, adjunctive antimicrobial agents are frequently incorporated to establish a "mechano-chemical" therapeutic approach[16,120]. Given its high absorption by water, ability to treat both soft and hard tissues, and minimal thermal side effects, the Er:YAG laser has been widely adopted in periodontics. It facilitates root surface debridement, calculus removal, bacterial reduction, and biostimulation through photothermal and photomechanical effects. Its clinical applications include traditional flap surgery, regenerative procedures (Er-Laser-Assisted Periodontal Regeneration Therapy, Er-LBRT), and minimally invasive non-flap techniques (Er-Laser-Assisted Comprehensive Periodontal Therapy, Er-LCPT). Mechanistic evidence demonstrate its efficacy in significantly reducing probing depth (PD), improving clinical attachment level (CAL), and, in certain situations, achieving superior bone regeneration outcomes compared with conventional mechanical therapy[121-125]. The following section systematically reviews its current applications, research progress, and clinical value, with a focus on nonsurgical therapy and periodontal surgery.

2.2.1 *Nonsurgical periodontal therapy*

In nonsurgical periodontal therapy, lasers contribute by debriding infected tissue, achieving hemostasis, disinfecting, and promoting tissue healing, thereby serving as an adjunct to supragingival scaling and, more notably, subgingival SRP[126,127]. Zhu[128] demonstrated that the combined use of Er:YAG and Nd:YAG lasers with SRP for severe periodontitis effectively improved CAL in moderate-to-deep pockets over a short-term period, supporting its clinical application. Cheng[129] suggested that the combination of the Er:YAG laser and low-level laser therapy may have potential efficacy in mitigating inflammation associated with periodontitis, particularly in patients with deep periodontal pockets. Moreover, Aoki[130] reported that the Er:YAG laser was more effective than SRP alone in managing residual pockets. Conversely, Gurpegui Abud[131] found that low-energy (50 mJ) Er:YAG laser-assisted SRP yielded 3-month clinical outcomes comparable to those of conventional SRP in patients with moderate-to-severe chronic periodontitis, with the additional advantages of shorter treatment duration, reduced postoperative sensitivity, and higher patient acceptance, positioning it as a viable option for nonsurgical therapy. However, Schwarz[132] noted that although the Er:YAG laser offers potential benefits in debridement, antibacterial action, endotoxin removal, and root surface conditioning, it did not demonstrate superior clinical outcomes compared with SRP followed by EDTA application. Follow-up durations varied across the aforementioned studies.

Meanwhile, *in vitro* studies have shown that lasers can selectively remove dental calculus with high precision through a "photomechanical effect." The 2940 nm wavelength is highly absorbed by water within the calculus, generating micro-explosions

that disintegrate the deposits. In contrast, the underlying cementum, because of its higher mineral content and lower water content, absorbs minimal laser energy, resulting in negligible damage[129,133-135]. Agoob Alfergany[136] reported that erbium lasers exhibited greater calculus removal efficacy than hand or ultrasonic instruments, with the Er:YAG laser being significantly more efficient than the Er,Cr:YSGG laser. Fried[137] explored the feasibility of using short-wave infrared reflectance imaging to guide a diode-pumped solid-state Er:YAG laser for selective calculus ablation while minimizing damage to healthy cementum and dentin. Their results suggested the potential of this diode-pumped solid-state Er:YAG laser ablation technique; however, further optimization is required to address residual deposits and localized tissue damage. However, Eberhard[138], who compared the efficacy of the Er:YAG laser with conventional SRP for subgingival calculus removal in patients with periodontitis, concluded that although the laser could effectively remove subgingival calculus in a clinical *in situ* setting, its removal efficacy was significantly lower than that of conventional SRP. Extending the laser application time only partially improved the outcome.

In summary, lasers demonstrate dual potential in nonsurgical periodontal therapy. First, as an adjunct or alternative to traditional SRP, lasers such as the Er:YAG can effectively debride, disinfect, and promote healing. As shown in Figure 2, this integrated therapeutic concept involves laser-mediated debridement, bacterial reduction, and potential biostimulation within the periodontal pocket. Some studies report clinical efficacy comparable to that of SRP, with additional benefits including shorter treatment time, reduced postoperative sensitivity, and higher patient acceptance. Second, considering their unique photomechanical effect, Er:YAG lasers offer the potential for high-precision, selective calculus removal with minimal damage to healthy root structures. However, evidence regarding their removal efficiency remains inconsistent. Therefore, clinical application parameters and overall efficacy require further optimization and validation.

2.2.2 Periodontal surgery

Periodontal surgery encompasses a range of surgical interventions performed following initial therapy to manage moderate-to-severe periodontal defects that are not responsive to nonsurgical management. The core objectives are to eliminate infection, repair periodontal supporting tissues, reconstruct periodontal health, and ultimately preserve the natural dentition[139,140]. Common procedures include periodontal flap surgery, guided tissue regeneration, gingivectomy, and crown lengthening surgery[141,142]. These procedures are broadly categorized into soft tissue incision or contouring and bone tissue management. The Er:YAG laser offers distinct advantages in periodontal surgery, enabling precise soft tissue ablation combined with concurrent subgingival debridement and root planing, as well as bone resection and contouring, often with minimal gingival recession and postoperative complications[143,144].

2.2.2.1 Soft tissue incision and contouring

Elafifi Ebeid[143] reported that Er:YAG and Er,Cr:YSGG laser-assisted flapless crown lengthening surgery provided excellent gingival margin stability and postoperative pain control with reduced tissue trauma. However, complications such as bone grooves and root surface pitting were noted, underscoring the need for standardized operative techniques. A randomized controlled trial by Sculean[145] showed no statistically significant difference in PD reduction or CAL gain between the Er:YAG laser and conventional ultrasonic groups at 6 months, although a trend toward greater bone regeneration was observed in the laser group. Connective tissue grafting remains the gold standard for treating gingival recession and augmenting peri-implant soft tissue. However, traditional epithelial removal methods may leave residual epithelium (up to 80%), potentially leading to complications such as cyst formation at the recipient site. Hazrati[146] demonstrated that laser-assisted de-epithelialization of free gingival grafts achieved clinical outcomes comparable to those of the traditional scalpel technique, with advantages in esthetics and operative efficiency and a favorable safety profile.

2.2.2.2 Bone contouring and regeneration

Schwarz[132] compared the treatment of deep intrabony defects using an Er:YAG laser combined with enamel matrix derivative (EMD) versus conventional SRP followed by EDTA and EMD application. The results indicated that the Er:YAG + EMD group achieved regenerative outcomes comparable to those of the SRP + EDTA + EMD group, with no significant differences in clinical parameters such as PD reduction and CAL gain. Taniguchi[147] developed a novel approach termed Er-LBRT for periodontal regeneration without the use of a barrier membrane. This technique utilizes the Er:YAG laser for root surface debridement and is proposed to enhance blood clot stabilization on the grafted bone surface. In their study, nine intrabony defects in six patients were treated with EMD combined with autogenous bone grafting using Er-LBRT. At 12 months postoperatively, the mean PD significantly improved from 6.2 mm to 2.0 mm. Lin[148] applied Er-LBRT combined with freeze-dried bone allograft for the treatment of class III furcation defects. Although complete furcation closure was not achieved, significant bone regeneration within the defect area was observed. However, these findings should be interpreted with caution, as the studies reporting positive bone regeneration outcomes are small-sample exploratory trials or case reports[147,148]. Although the results are encouraging and demonstrate technical feasibility, the limited sample sizes are insufficient to establish the generalizable efficacy of the Er:YAG laser in promoting periodontal bone regeneration. Therefore, these preliminary observations require validation through larger-scale, well-controlled clinical trials.

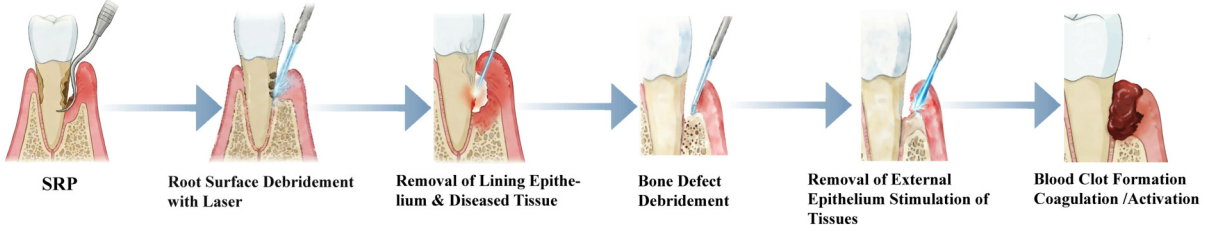

Figure 2 The schematic illustrates application of Er:YAG laser in periodontal non-surgical therapy.

In summary, the Er:YAG laser provides a minimally invasive and efficient adjunctive approach to periodontal therapy, effectively addressing several limitations of conventional techniques. However, the current evidence is predominantly based on clinical trials with small sample sizes, highlighting the lack of large-scale, multicenter randomized controlled trials. Furthermore, the molecular mechanisms underlying its biostimulatory effects are not fully elucidated, with most evidence derived from *in vitro* studies. In addition, the technique presents practical challenges, including a steep learning curve and high equipment costs, which necessitate a thorough cost–benefit analysis for routine clinical implementation. Future research should focus on large-scale randomized controlled trials with standardized laser parameters and clearly defined patient selection criteria to establish evidence-based clinical protocols.

Overall, in both nonsurgical and surgical periodontal therapy, the Er:YAG laser demonstrates potential as an adjunctive tool for debridement, antibacterial action, and promotion of healing. While some studies suggest that its clinical outcomes are comparable to those of conventional SRP, with advantages such as reduced postoperative discomfort and higher patient acceptance, its efficacy in calculus removal remains debated. Current evidence is largely derived from small-scale studies with variable laser parameters, limiting direct comparability across studies. Future multicenter, large-sample trials, together with mechanistic investigations, are needed to establish evidence-based clinical guidelines.

2.3 Implantology and prosthodontics

Peri-implantitis is a pathological inflammatory condition affecting the tissues surrounding a dental implant, accompanied by progressive loss of supporting bone[149,150]. Its estimated prevalence is approximately 20% at the patient level[151]. A standardized treatment protocol is currently lacking. Advanced cases often require surgical intervention; however, the efficacy of traditional regenerative surgery is limited by unpredictable implant surface decontamination and overall prognosis[152-154]. In recent years, laser therapy has gained attention as a promising alternative or adjunctive treatment for peri-implantitis due to its ability to selectively decontaminate implant surfaces while minimizing damage to surrounding tissues[155,156]. Among various laser systems, the Er:YAG laser is frequently favored due to its high affinity for water[157], enabling effective removal of bacterial biofilm and granulation tissue with minimal thermal damage[158].

2.3.1 Bone defect repair

Non-surgical therapy, including ultrasonic debridement, air abrasion, and chemical decontamination, is typically the first-line approach but has limited efficacy in advanced cases[159,160]. In severe presentations, surgical interventions such as access flap surgery with or without regenerative procedures may be indicated, although clinical outcomes are variable and potential risks remain[161-163]. Guided bone regeneration for intrabony defects associated with peri-implant lesions has shown promise[161]. While surgical management of peri-implant bone defects is supported by numerous studies, complete resolution of the lesion or defect resolution remains unpredictable[164,165]. A primary challenge lies in effectively decontaminating the implant surface, particularly those with micro-rough or threaded topographies[166]. *In vitro* studies have confirmed that the Er:YAG laser can exert bactericidal effects, remove inflammatory tissue, achieve hemostasis, and potentially stimulate wound healing without altering implant surface microstructure[167-169]. Wang[170] evaluated the additional clinical benefit of the Er:YAG laser as an adjunct to regenerative surgery for peri-implantitis-associated bone defects. Their results indicated that Er:YAG laser-assisted regenerative surgery significantly improved PD reduction in patients with peri-implantitis but did not demonstrate statistical superiority in CAL gain or bone regeneration. The clinical efficacy of photobiomodulation in managing experimental peri-implant bone defects remains unclear, as noted by Javed[171]. Although the Er:YAG laser demonstrates clinical value as an adjunctive tool for implant surface debridement, its capacity to independently promote peri-implant bone regeneration is not supported by robust high-level evidence. Current positive findings are largely derived from studies with limited sample sizes, whereas higher-level evidence from randomized controlled trials presents mixed or inconsistent results[170]. Clinicians should therefore maintain realistic expectations regarding its role in bone regeneration.

2.3.2 Inflammation control

Antimicrobial PDT, which utilizes a photosensitizer activated by a specific light wavelength to generate bactericidal reactive oxygen species, serves as an adjunct to mechanical debridement and aims to enhance treatment outcomes while circumventing antibiotic resistance[172-174]. Jervøe-Storm[175] concluded that current evidence does not support the routine use of antimicrobial PDT as an adjunct in periodontal therapy, highlighting the need for larger-scale, low-bias randomized controlled trials, particularly in patients with peri-implantitis. Dai[176] identified 80 mJ as the optimal Er:YAG laser energy parameter for treating peri-implantitis, effectively removing plaque biofilm, reducing inflammation, and alleviating pain, with efficacy superior to that of minocycline hydrochloride. Schwarz[177] investigated the impact of two surface decontamination methods—Er:YAG laser versus plastic curettes plus sterile saline-soaked cotton pellets—combined with surgical therapy on clinical outcomes in moderate-to-severe peri-implantitis. Both decontamination methods, when combined with surgery, significantly improved short-term (6-month) clinical outcomes and radiographic bone regeneration.

2.3.3 Material modification and prosthesis bonding

The bonding of restorative materials such as resins, ceramics, and metals requires high performance. Various surface pretreatment methods have been proposed for ceramics, including air-particle abrasion, chemical etching, and silica coating[178,179]. Among chemical etching agents, hydrofluoric acid (HF), acidulated phosphate fluoride, and ammonium hydrogen fluoride have been reported to enhance micromechanical retention[180]. Acidic gels offer clinical convenience for chairside ceramic etching and have been shown to provide favorable retention[181]. For resin-based composites, surface treatments such as grinding with diamond burs or silicon carbide papers, tribochemical coating, air-particle abrasion with alumina, acid etching, silane coupling, and adhesive system application have been shown to enhance bond strength[182-186]. Laser irradiation, which increases surface roughness to promote micromechanical retention, has been proposed as an alternative surface treatment strategy for composite, ceramic, or resin-matrix ceramic restorations[187,188]. The laser energy is absorbed by water, leading to particle removal and micro-pore formation on the material surface, particularly within its inorganic components, via a micro-explosive effect[180,189].

Gökçe[190] reported that both 9.5% HF acid etching and 300 mJ

Er:YAG laser etching significantly increased the SBS of lithium-based glass ceramics. However, a negative correlation was observed between laser power and SBS, as higher energy levels caused severe crystalline disruption and excessive surface irregularity, reducing bond strength to levels below those of the control group. Önöral[191] emphasized that the choice of surface treatment for resin-matrix ceramics depends on the material type, with laser irradiation being a viable alternative to air abrasion, requiring a balance between surface roughness (for bonding) and mechanical integrity (for restoration durability).

Teeth with compromised structural integrity following RCT often require quartz fiber posts (QFPs) to ensure restorative stability[192,193]. The elastic modulus of QFPs is similar to that of dentin, reducing the risk of root fracture. However, the post space must be thoroughly cleaned of the smear layer; otherwise, the push-out bond strength between the QFP and radicular dentin may be compromised[194,195]. Traditional disinfection protocols using 2.5% NaOCl and 17% EDTA have limitations: NaOCl is cytotoxic and may interfere with resin polymerization, while EDTA may cause dentin erosion, prompting the search for superior alternatives[196,197]. Modern treatment strategies incorporate a multimodal approach, including Er:YAG laser for physical debridement, Pc-PDT for targeted chemical disinfection, and bioactive glass nanoparticles for long-term antibacterial and bioactive effects, forming a comprehensive minimally invasive synergistic concept. Moreover, Mahmoud[110] demonstrated that Er:YAG laser treatment followed by EDTA irrigation yielded the highest push-out bond strength between QFPs and root dentin. Alkhudhairy[198] proposed that Pc photosensitizer-doped chitosan nanoparticle-mediated PDT combined with EDTA could serve as a suitable alternative to NaOCl for root canal disinfection, effectively removing the smear layer and enhancing glass fiber post bond strength.

In summary, the Er:YAG laser provides a minimally invasive, precise, and low-thermal-damage approach to addressing key challenges in implantology and prosthodontics, including peri-implantitis-associated bone defects, persistent inflammation, and insufficient restorative bond strength. It serves as an important adjunct and optimization to conventional therapies. When used as an adjunct in regenerative surgery for peri-implant bone defects, the Er:YAG laser can significantly improve clinical parameters such as PD. It achieves bactericidal and biostimulatory effects while preserving implant surface microstructure. An energy setting of 80 mJ appears optimal for peri-implantitis treatment. When combined with surgery, this protocol can effectively control inflammation, enhance bone fill, and avoid contributing to antibiotic resistance. Although laser debridement is considered safer for the implant surface, the long-term effects of repeated or high-energy irradiation on the implant–bone interface remain insufficiently understood. In regenerative surgery, if not properly controlled, thermal effects of the laser may adversely affect the viability of graft materials or surrounding osteogenic cells. Furthermore, the success rate of laser therapy for peri-implantitis is not absolute, and its efficacy remains uncertain in complex cases with severe bone defects and mucosal hyperplasia, which may require combination with more advanced surgical interventions. In material modification and prosthesis bonding, the Er:YAG laser serves as an effective alternative to traditional methods such as air-particle abrasion and HF etching. By modifying surface topography, it can improve bond strength. However, individualized strategies and energy settings must be tailored to specific materials to balance bonding efficacy with restoration durability. Future directions should focus on optimizing synergistic protocols combining lasers with regenerative techniques and antibacterial materials, while also establishing standardized and individualized parameter guidelines to fully realize their clinical value in implantology and prosthodontics.

2.4 Oral and maxillofacial surgery

Oral and maxillofacial surgery encompasses the management of pathologies affecting the craniofacial region, including tumors, deformities, and dentition defects. Conventional approaches are often associated with significant trauma, substantial bleeding, a high risk of nerve injury, and prolonged postoperative recovery[199-201]. Since their introduction into surgery in the 1960s[202], lasers—particularly the Er:YAG laser—have demonstrated unique value in minimally invasive maxillofacial procedures. By leveraging the photomechanical effect for precise cutting, the thermal effect for hemostasis and disinfection, and potential biostimulation, the Er:YAG laser can significantly reduce surgical trauma, minimize complications, and accelerate wound healing[203-205]. This section systematically reviews its current applications, research progress, and clinical value in three key areas: tumor management, exodontia, and vascular malformation treatment.

2.4.1 Tumor management

Taking oral leukoplakia, a WHO-recognized potentially malignant disorder, as an example, common treatments include medication, surgical excision, cryotherapy, and laser therapy. Lasers primarily exert their effects in tumor management through photothermal mechanisms[206,207]. When laser energy is absorbed by tissue water, it is converted into heat, enabling tissue coagulation and ablation[208,209]. Liu[210] compared the clinical efficacy of Er:YAG and CO_2 lasers for oral tumorous lesions. The Er:YAG laser group demonstrated a significantly higher treatment success rate but a longer operative time. No significant differences were observed in recurrence or complication rates. Luo[211] compared various lasers with surgical excision for oral leukoplakia. The Er,Cr:YSGG laser showed the lowest postoperative recurrence rate, the Er:YAG laser was optimal for intraoperative hemostasis, and the Er,Cr:YSGG laser resulted in the lowest pain score on the first postoperative day. CO_2 laser combined with PDT also showed favorable anti-recurrence effects. Overall, all laser modalities were superior to surgical excision in terms of intraoperative bleeding and postoperative pain, with no serious adverse events reported, positioning them as effective alternatives that reduce recurrence risk and improve patient comfort.

2.4.2 Tooth extraction

Tooth extraction, especially of impacted third molars and residual roots, is a routine procedure. Traditional methods may cause significant hard and soft tissue damage and are associated with frequent postoperative complications[212,213]. The Er:YAG laser can optimize the extraction process and outcomes through precise cutting, hemostasis, and disinfection[214].

Larionova[214] evaluated the Er:YAG laser for tooth extractions in patients with hemostatic disorders. The two-stage laser protocol involved circumferential periodontal ligament incision followed by socket curettage. The laser group showed significantly shorter hemostasis time, less postoperative pain and edema, faster socket epithelialization, and a comparable incidence of postoperative bleeding compared with the conventional group, indicating a safe

and effective method for high-risk patients. However, Pillai[215] compared conventional surgical extraction with minimally invasive techniques, including piezosurgery, laser-assisted extraction, and methods utilizing three-dimensional (3D) imaging and navigation. They found that piezosurgery, and particularly 3D imaging- or navigation-guided extraction, resulted in shorter operative times, lower intraoperative complication rates, and improved postoperative outcomes (reduced pain, less swelling, and faster healing) compared with both conventional and laser-assisted extraction, suggesting potentially superior alternatives.

2.4.3 Vascular malformations

Vascular malformations (e.g., venous, capillary, and lymphatic) in the maxillofacial region are congenital lesions presenting as localized tissue swelling and discoloration. They are difficult to completely eradicate with traditional therapies, which are associated with a relatively high risk of complications[216,217]. The Er:YAG laser achieves minimally invasive treatment by inducing thermal coagulation and occluding abnormal vessels, serving as an important adjunct to conventional methods[218].

Loranger[219] presented a case report in which a superficial microcystic lymphatic malformation was treated over eight sessions using a fractional ablative 2940 nm Er:YAG laser, combined with preoperative imaging assessment (ultrasound and magnetic resonance imaging) and postoperative care. The treatment resulted in 75%–90% improvement in appearance, significant reduction in pain and leakage, absence of scarring, and only mild pigmentation. A 22-month follow-up showed mild recurrence, suggesting the need for maintenance therapy, but confirming the laser's effectiveness for superficial lesions with a priority on minimizing scarring risk. Moreover, Pellegrini[220] in a retrospective study, reported that the Nd:YAG laser was highly effective for deep oral vascular malformations, the diode laser excelled in coagulation with less postoperative discomfort, the Er,Cr:YSGG laser promoted faster healing with favorable esthetic outcomes, and the CO_2 laser was associated with low recurrence rates. All laser modalities reduced bleeding, pain, and recovery time. The study confirmed these lasers as safe and effective minimally invasive options but noted limitations such as small sample sizes and lack of randomized controlled trials, highlighting the need for larger studies comparing laser-based and conventional therapies.

The management of vascular malformations, particularly in the oral region, remains complex. No universally accepted treatment protocol exists, as the optimal approach depends on lesion size, depth, location, and patient-specific factors. Despite these challenges, laser technology continues to evolve, with ongoing research focusing on optimizing parameters, improving long-term esthetic outcomes, and reducing recurrence risk.

2.4.4 Medication-Related Osteonecrosis of the Jaw (MRONJ)

Bisphosphonates, drugs that inhibit osteoclast-mediated bone resorption, are widely used for conditions such as bone metastases, osteolytic bone diseases, tumor-induced hypercalcemia, and osteoporosis[221,222]. Their benefits include pain reduction and improved quality of life[223]. However, adverse effects such as inhibition of angiogenesis, induction of bone necrosis, and impaired macrophage function can lead to MRONJ[224]. Current treatments include systemic antibiotics, irrigation, and surgical interventions such as debridement or resection, although outcomes remain inconsistent. Laser therapy has emerged as a potential alternative approach[225]. The Er:YAG laser offers specific advantages. Its wavelength and irradiation modes exert antibacterial effects, reducing bacterial load in necrotic areas and lowering infection risk[226]. Its non-contact ablation minimizes mechanical friction and thermal trauma associated with conventional surgery, thereby preserving bone cell viability. In addition, it enables precise removal of necrotic bone while preserving the microtrabecular architecture of viable bone, reducing the risk of over-preparation[227-229].

Stübinger[227] used a VSP Er:YAG laser to ablate necrotic bone in patients with MRONJ. All procedures were complication-free, with no thermal damage or injury to adjacent soft tissues. Complete soft tissue healing with normal epithelial coverage occurred within 4 weeks. Laser ablation produced a characteristically microstructured, rough bone surface without a smear layer and preserved the trabecular architecture of the remaining vital bone, providing an optimal substrate for cellular colonization. Vescovi[228] reported a combined protocol using piezosurgery, Er:YAG laser ablation, and Nd:YAG laser photobiomodulation for stage 3 MRONJ, achieving rapid short-term recovery (mucosal healing within 1 month) and long-term stability (no recurrence beyond 4 years), with effective pain control. This multimodal approach was presented as a promising alternative to conventional treatment strategies. A case report by de Freitas[229] described successful surgical removal of necrotic bone using an Er:YAG laser, with no signs of recurrence during follow-up, supporting laser therapy as an effective alternative approach. These preliminary clinical reports describe the use of the Er:YAG laser for precise debridement, reduced intraoperative bleeding, and enhanced soft tissue healing. However, no randomized controlled trials have yet compared the efficacy and outcomes of laser-based approaches with those of conventional surgical methods.

In oral and maxillofacial surgery, the Er:YAG laser, with its core advantages of precision, minimal invasiveness, and low thermal damage, effectively addresses limitations of traditional surgery such as high trauma, significant bleeding, and frequent complications[230]. It serves as a suitable option for superficial small tumors and cases with high esthetic demands in benign tumor management; significantly reduces postoperative sequelae and the risk of alveolar osteitis in complex extractions; and balances efficacy with cosmetic outcomes in the treatment of superficial vascular malformations. The common mechanism underlying these effects is the synergistic application of photomechanical and thermal interactions to facilitate wound healing. Current limitations primarily involve high equipment costs and potentially reduced efficiency or efficacy for large-volume or deeply seated lesions. Future advancements should focus on technological innovation to reduce costs, optimize parameters, and develop combined treatment strategies to further expand its application in complex maxillofacial cases, driving the field toward an era of "ultra-minimally invasive, function-preserving, and esthetic-oriented" surgery.

2.5 Other applications

Beyond the aforementioned fields, the Er:YAG laser also demonstrates precise tissue interaction and minimally invasive advantages, exhibiting broad potential in orthodontics, oral mucosal disease management, and pain control[231-233]. This section systematically reviews its current applications, research progress, and clinical value in these three core areas.

2.5.1 Orthodontics

In fixed orthodontic treatment, enamel pretreatment is required for

bracket bonding. The gold standard, 37% phosphoric acid (PA) etching, carries risks of DH and enamel damage[234]. Furthermore, the presence of brackets, archwires, and bands complicates oral hygiene maintenance, promoting plaque accumulation and increasing the risk of demineralization[235-237]. Çokakoğlu[238] investigated the effects of different Er:YAG laser parameters (100 mJ/1 W and 200 mJ/2 W, both at 10 Hz) combined with three adhesive systems on enamel demineralization and SBS. They found that Er:YAG laser at 1 W/100 mJ combined with a two-step self-etch adhesive could effectively prevent demineralization while maintaining adequate bracket SBS.

The demand for orthodontic treatment among adults is increasing, and many patients present with porcelain crowns, which complicates bracket bonding. Optimal adhesion to porcelain is crucial to ensure bracket retention during treatment while preserving the integrity of the porcelain surface during debonding. Thus, bonding to porcelain represents a clinical challenge in orthodontics, requiring a balance between sufficient adhesion strength to prevent debonding and controlled adhesion to allow clean removal at the end of treatment. Since their introduction into dentistry in the 1960s, lasers have been widely used in medical and dental applications. In orthodontics, various laser systems have been proposed for enamel surface preparation prior to bracket bonding[239].

Yassaei[231] compared the SBS of orthodontic brackets bonded to porcelain surfaces etched with an Er:YAG laser versus 9.6% HF. They concluded that the Er:YAG laser could serve as a suitable alternative to HF, with 1.6 W power showing optimal results. However, Mirhashemi[240] compared the effects of Er:YAG and Er,Cr:YSGG lasers (with and without HF etching) versus HF alone on the SBS of brackets bonded to porcelain. The HF-only group showed the highest SBS. Groups combining HF with either laser showed no significant difference from HF alone. The Er,Cr:YSGG-only group reached the acceptable orthodontic bond strength threshold, whereas the Er:YAG-only group did so inconsistently. SEM analysis revealed deeper etching patterns in the HF group compared with the laser groups, suggesting that the Er:YAG laser alone is not a suitable replacement for HF, and that the Er,Cr:YSGG laser requires further optimization to serve as a potential alternative.

In summary, in fixed orthodontic treatment, laser technologies such as the Er:YAG laser demonstrate potential to replace traditional pretreatment methods in certain bonding situations. Low-energy Er:YAG laser combined with self-etch adhesives can effectively prevent demineralization while providing sufficient bond strength. For bonding to restorations such as porcelain crowns, although bond strength achieved with Er:YAG laser alone is inconsistent and most studies still support the superiority of traditional HF etching, some findings indicate that the Er,Cr:YSGG laser or a combination of Er:YAG laser with HF can achieve clinically acceptable bond strength. This suggests that, with parameter optimization, laser technology may represent a viable alternative for bonding to ceramic surfaces.

2.5.2 *Oral mucosal diseases*

Oral lichen planus (OLP) is a chronic inflammatory disease that commonly affects the oral mucosal surfaces but may also involve extraoral epithelial sites such as the skin, genitalia, nails, and scalp. The buccal mucosa is most frequently affected, followed by the tongue, gingiva, and vermilion border of the lower lip[241]. The disease is more common in women aged 50–60 years[242], but it can also affect individuals under 18 years, in whom the clinical features are similar, although the prognosis is generally more favorable[243]. Although OLP may resolve spontaneously, many lesions require treatment. The most commonly used medications are topical corticosteroids. Intralesional injections and systemic corticosteroids are also employed. Other topical and systemic agents include immunosuppressants (e.g., cyclosporine, tacrolimus) and retinoids administered topically or systemically. Refractory cases have been treated with agents such as thalidomide and non-pharmacological therapies such as psoralen plus ultraviolet A[244,245]. Given the malignant potential of OLP, management strategies for this potentially malignant disorder vary. Some clinicians advocate traditional surgical excision, sometimes followed by free gingival grafting for reconstruction. Others recommend cryosurgery as an alternative to scalpel excision, a technique particularly suited to the moist and delicate nature of oral mucosal tissue. Additionally, for patients experiencing spontaneous pain during meals that is unresponsive to topical corticosteroids, laser vaporization of OLP lesions can provide long-term symptom relief and may be considered a treatment option in such cases[246-249].

Fornaini was among the first to propose the use of the Er:YAG laser for OLP treatment[250]. In a case report, they demonstrated the effectiveness of the Er:YAG laser in reducing OLP symptoms and lymphoplasmacytic infiltration, suggesting it as a potential treatment option for non-erosive OLP, with advantages including rapid healing and minimal discomfort. Tarasenko[251] compared the clinical efficacy of different high-power lasers with traditional scalpel excision for erosive OLP. High-level laser therapy, particularly using the Er:YAG laser, was significantly superior to scalpel excision in reducing inflammatory cytokines, alleviating pain, and accelerating epithelialization.

Oral candidiasis is an opportunistic infection primarily caused by *Candida* species[252], with *Candida albicans* being the most common pathogen[253-255]. Its development is influenced by a range of local and systemic predisposing factors that disrupt host–microbial homeostasis[256-258]. Non-albicans *Candida* species can form multispecies biofilms with bacteria such as *Streptococcus gordonii*, *S. salivarius*, and *S. oralis*, enhancing their resistance to antifungal agents due to cell wall alterations, including reduced ergosterol content and modified β-glucan structure. Treatment challenges include inadequate antifungal dosing and premature discontinuation, leading to infection recurrence and the need for prolonged therapy[255,259,260]. Given these challenges, alternative therapeutic strategies to complement or replace traditional antifungal agents are needed. Promising approaches include chlorhexidine, cetylpyridinium chloride, sanguinarine, octenidine, heavy metal nanoparticles, ozone therapy, and laser therapy[261-267]. Among these, laser therapy has gained increasing attention. High-power lasers, including diode, Nd:YAG, Er:YAG, and Er,Cr:YSGG systems, have demonstrated antimicrobial efficacy[88,268-273].

Dembicka-Mączka[274] evaluated the disinfectant effect of the Er:YAG laser on single-species *Candida* biofilms. They found that even at low energy (50 mJ), the laser inhibited biofilm growth, whereas 150 mJ was optimal for eliminating mature biofilms, suggesting a potential alternative approach for drug-resistant oral candidiasis, although further *in vivo* studies are required to confirm clinical applicability. Grzech-Leśniak[232] assessed the antimicrobial effect of the Er:YAG laser on mono- and dual-species biofilms containing *C. albicans*, *C. glabrata*, and *S. mutans*, confirming its

efficacy in reducing biofilm viability. However, the clinical relevance and applicability of these *in vitro* findings require validation through *in vivo* studies and clinical trials.

Current evidence demonstrates promising therapeutic potential of the Er:YAG laser for both OLP and oral candidiasis. For OLP, particularly erosive forms with limited response to conventional medication or associated pain, the Er:YAG laser can effectively alleviate symptoms, reduce inflammation, and promote healing, offering a less traumatic alternative to surgical excision[249-251]. Regarding oral candidiasis, especially cases involving biofilm formation and drug resistance, *in vitro* studies confirm its antifungal and biofilm-disrupting effects at various energy settings, providing an experimental basis for its use as an adjunct or alternative to traditional antifungal therapies[232,268,274]. However, a critical note on clinical application is warranted. For potentially malignant disorders such as OLP, laser therapy serves as a local intervention aimed at symptom control, elimination of clinically visible lesions, and improvement of quality of life. It does not eliminate the underlying risk of malignant transformation. Therefore, regardless of the treatment modality (including laser therapy), regular long-term follow-up and surveillance of patients with OLP are essential for the early detection of any signs of malignant change[241,242]. Clinicians should incorporate this risk and the need for ongoing monitoring into the informed consent process and overall management plan prior to offering laser treatment. In summary, the Er:YAG laser represents a promising tool in the management of OLP and oral candidiasis; however, its application must be integrated within a comprehensive understanding of disease biology and adherence to standardized long-term clinical management protocols.

2.5.3 *Pain management*

A core objective of RCT is the complete elimination of infection within the root canal system and the prevention of reinfection. Despite advances in instrumentation and irrigation protocols, postoperative pain remains a common complication, with a reported incidence of up to 58%[275]. This post-treatment pain is not only frequent but also varies widely in intensity. Data from randomized clinical trials indicate that the average VAS pain score within 24 hours after treatment typically ranges from 2 to 4 (out of 10), with pain generally subsiding over time[276-281]. Factors influencing postoperative pain are multifactorial, including instrument type, analgesic use, extrusion of debris or irrigant beyond the apex, preoperative pulp status (symptomatic or asymptomatic), and patient-specific host factors. To reduce postoperative pain and enhance disinfection, advanced irrigation techniques such as UAI and LAI have been explored. UAI utilizes acoustic streaming and cavitation, whereas LAI leverages photomechanical and photoacoustic effects to enhance irrigant penetration. Various laser systems have been investigated for their ability to improve cleaning and disinfection in complex root canal anatomies[277,278].

Sabeti[233] demonstrated that LAI provided a statistically and clinically significant advantage in reducing postoperative pain after RCT, with the most pronounced effects observed at 24–48 hours, particularly with the pulsed Er:YAG laser, especially in SWEEPS mode. Moreover, Mathevanan[281] in a randomized, double-blind, parallel-group clinical trial, found that both PUI and LAI were effective in alleviating postoperative pain and reducing analgesic intake, with PUI showing a slight advantage over LAI. Mittal[280] evaluated the impact of different irrigation activation systems on postoperative pain and reported lower pain scores with LAI compared with other systems. Krishnakumar[278] found that continuous ultrasonic irrigation, LAI, and laser irradiation all effectively reduced inter-appointment pain at 24 and 48 hours, with pain becoming negligible by day 7 in all groups and no statistically significant differences among the three techniques in pain incidence, pain scores, or analgesic consumption. Erkan[276] reported that LAI techniques (PIPS and SWEEPS) were most effective in controlling postoperative pain after RCT. Conversely, Kaplan[277] found that the use of the EDDY sonic activation system or a 980 nm diode laser for disinfection did not significantly reduce postoperative pain levels or analgesic intake in mandibular molars with symptomatic apical periodontitis. Multiple *in vitro* studies consistently demonstrate that Er:YAG LAI significantly outperforms CNI in smear layer removal and biofilm elimination, particularly within complex root canal anatomy. This preclinical evidence provides a mechanistic rationale for its clinical application. However, while existing clinical research has primarily focused on postoperative pain outcomes, higher-level evidence regarding its ability to improve definitive treatment success, such as periapical healing, is still emerging.

In summary, conclusions regarding the analgesic efficacy of different irrigation techniques vary across studies. Overall, pulsed Er:YAG laser–based LAI techniques are supported by most studies as a favorable option for postoperative pain control. The choice of irrigation method in clinical practice should consider device availability and patient-specific clinical conditions.

3 Future perspectives

A systematic review and analysis of Er:YAG laser applications across various dental disciplines underscores its transformative role as a precise, minimally invasive, and highly efficient diagnostic and therapeutic tool (Table 1). The laser not only significantly enhances patient comfort and procedural controllability but also exhibits unique advantages in infection control, tissue preservation, and functional regeneration.

In reviewing its applications across specialties, the value of the Er:YAG laser lies not only in supplementing or replacing conventional techniques, but also in providing oral medicine with a unified, minimally invasive treatment philosophy grounded in tissue biophysics. This shared foundation positions it as a platform technology for integrated, multidisciplinary treatment strategies. From selective caries removal and periodontal pocket debridement to implant surface decontamination and resection of osteonecrotic jaw lesions, the laser provides a continuum of controllable ablation spanning dental hard tissues to maxillofacial bone. This enables the use of a single device and coherent technique in managing complex cases involving multiple tissue types, such as severe endodontic–periodontal lesions or peri-implantitis with extensive soft tissue hyperplasia and bone defects, thereby reducing the need to switch modalities and minimizing cumulative trauma. Although the level of evidence requires further strengthening, the laser has been reported to exhibit potential biomodulatory effects in pulp healing, periodontal regeneration, and bone defect repair. This suggests that in various regenerative therapies, such as VPT, guided tissue regeneration, and peri-implant bone augmentation, the laser may function as a common biophysical modulator, acting synergistically with bioactive materials to optimize the healing environment.

Table 1 Common application details of Er:YAG laser in oral medicine.

Application	Pulse Energy (mJ)	Time	Frequency (Hz)	Notes
Caries removal	Enamel: 250–300 Superficial dentin: 200–250 Deep dentin: 100–200	Enamel: 10–15 s/cm^2 Dentin: 8–12 s/cm^2	Enamel: 25–30 Superficial dentin: 25–30 Deep dentin: 30–50	Non-contact irradiation: Maintain a 2 mm distance from the tooth surface to avoid contamination or concentrated energy from tip contact Scanning motion: avoid prolonged stationary focus on a single site Employ high-volume water spray with intermittent irradiation to minimize heat accumulation After caries removal, rinse the cavity with saline to remove ablation debris and prevent interference with bonding Low energy and high frequency
Management of dentin hypersensitivity	50–150	Single irradiation ≤ 3 s/site	10–30	Maintain continuous water cooling (flow rate ≥5 mL/min) Non-contact irradiation at 1–1.5 mm distance with scanning motion (speed 1–2 mm/s); avoid prolonged stationary focus Limit irradiation to the sensitive area only; avoid healthy enamel to prevent micro-cracks
Root canal activation & irrigation	100–200	30 s/canal	12–20	The tip must not contact the root canal walls Continuously replenish irrigant via syringe to ensure the tip remains submerged; avoid dry irradiation Control irrigation pressure to prevent irrigant extrusion beyond the apical foramen
Periodontal non-surgical therapy	40–150	As required	15–25	Use a 400 μm tip for narrow pockets and a 600 μm tip for wide pockets or external tissue; avoid contact with bone to prevent excessive ablation Water spray must be ON during intrasulcular procedures, and OFF during external epithelial removal and coagulum stabilization
Treatment of oral lichen planus	Ablation: 200 Coagulation: 300	15 s/cm^2	25–30	Activate air/water spray during ablation; deactivate during coagulation For ablation, use contact mode with a reciprocating motion for complete lesion removal For coagulation, use a defocused mode, avoiding direct contact with mucosa to prevent carbonization For deep lesions involving muscle layers, suturing is required post-operatively

While this review aims to provide a comprehensive overview of Er:YAG laser applications in oral medicine, several inherent limitations of the current literature must be acknowledged. First, there is considerable heterogeneity among the included studies. A substantial proportion of the evidence supporting specific mechanisms, such as biostimulation or antibacterial effects, originates from *in vitro* or animal studies, and its translatability to clinical settings remains uncertain. Furthermore, many clinical studies, particularly in emerging application areas, are limited to small case series, retrospective analyses, or preliminary reports, indicating the need for higher levels of evidence. Second, laser treatment parameters, including energy, frequency, pulse duration, and irradiation mode, vary widely across studies and generally lack standardization. This variability hinders direct comparison and meta-analysis of results and complicates the establishment of unified clinical guidelines. Third, data on long-term efficacy and safety remain limited. Most clinical studies have follow-up periods of 6–24 months, which are insufficient for evaluating disease recurrence, long-term stability of restorative materials (e.g., bonded restorations), or potential late adverse events. Finally, the high cost of equipment and the associated learning curve present practical barriers to widespread clinical adoption. Acknowledging these limitations does not negate the value of the Er:YAG laser but rather serves to accurately delineate the current evidence landscape and highlight the gaps that future high-quality research must address.

The future development of Er:YAG laser technology will focus on several key directions. First, standardization through evidence-based guidelines: high-quality clinical trials are needed to establish standardized treatment parameters and promote consistent clinical protocols and broader clinical adoption. Second, integration with intelligent systems: a key direction involves combining laser systems with real-time imaging modalities (e.g., optical coherence tomography) and artificial intelligence. This integration will enable the development of intelligent, closed-loop treatment systems, allowing precise and controlled interventions from diagnosis through therapy. Third, synergy with regenerative strategies: advancing interdisciplinary research on the biostimulatory mechanisms of laser energy in conjunction with tissue engineering and regenerative medicine is essential. This work aims to elucidate underlying biological pathways and fully harness the regenerative potential of Er:YAG lasers for craniofacial and periodontal tissue repair.

In conclusion, driven by continuous technological innovation and evolving conceptual paradigms, Er:YAG lasers are poised to provide improved solutions for the diagnosis and treatment of oral diseases, advancing oral medicine toward a future characterized by greater precision, minimal invasiveness, and personalization

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Data available statement

N/A

Author contribution

C.Z. designed the work. S.L. and J.A. wrote the initial draft of this paper. Y.L. organized the figures. The figures were created withBioGDP.com[282]. All the authors revised the manuscript and approved the final version.

Ethics approval and consent

N/A

Consent for publication

All authors agree to publish.

Conflicts of interest

The authors have no competing interests to declare that are relevant to the content of this article.

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