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THE USE OF ER:YAG LASER FOR DENTAL CARIES REMOVAL

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ABSTRACT

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Background Carious tissue removal in enamel and dentin requires the use of sharp and resistant instruments. New tools have appeared to optimize/facilitate dental treatment, among them the laser. Regarding laser application for dental caries removal, the use of erbium laser doped with yttrium, aluminum, and garnet (Er:YAG) stands out. The Er:YAG laser is excellent for hard tissues ablation since its wavelength of 2.940nm is highly absorbed by water and hydroxyapatite.
Objective To review the application of the Er:YAG laser in dental caries removal, to present its advantages and limitations in clinical practice, as well as to describe its action mechanism, and to compare its effectiveness with different methods used to remove caries.
Data sources The search for articles to compose this literature review was carried out in the PubMed and Embase databases.
Study selection Articles in English published between 2006 and 2021. The manual search included additional articles and books; a total of 39 references were selected.
Data extraction Information from studies that evaluated the use of the Er:YAG laser to remove caries or related this type of laser to other methods. Articles that evaluated characteristics of the dental structure, or the influence of restorative materials after caries removal with the Er:YAG laser, were also considered.
Study selection Based on studies results, the Er:YAG laser presents itself as an alternative for caries removal since it can remove demineralized tissue (selective ablation) without causing damage to the dental element.

KEYWORDS

Cariology; Dental Caries; Dental Caries Removal; Dentin; Lasers.

1. INTRODUCTION

Contemporary dentistry is based on early diagnosis, adequacy of the oral environment, and prevention of oral diseases. In recent years, new tools have emerged to optimize/facilitate dental treatment, including laser. Studies carried out over the years have proven the effectiveness of laser therapy for hard and soft tissues manipulation [1-3].
The word LASER comes from the English acronym Light Amplification by Stimulated Emission of Radiation. Its mechanism of action is based on the emission of a collimated light beam of high energy intensity and can be stimulated by solid, liquid, or gaseous active medium. Lasers have different wavelengths, and this implies the variable phenomena that they can present: absorption, penetration, transmission, and diffusion. In dentistry, the most desirable phenomenon is absorption, as it will interact with living tissue, effectively exercising its different functions [4].
Lasers can be classified, according to their application, in low and high-power lasers [4]. Low-power lasers can aid analgesia, reduce inflammation and stimulate tissue repair [3,5], while high-powered ones are used in surgery, ablation of decayed tissue, and orthodontics [2,4,5]. There are also lasers used for photodynamic therapy and tissue fluorescence diagnosis [4].
Regarding the application of laser for dental caries removal, the use of erbium-doped yttrium, aluminum, and garnet laser (Er:YAG laser) stands out. This laser operates in a pulsed mode, and the handpiece includes a spray of water to prevent tissue dryness and heat build-up, allowing energy to be absorbed efficiently [6].
Several types of research have evaluated the use of lasers in dentistry, highlighting the erbium laser in hard tissues [1,2,7,8]. This study aimed to perform a literature review about the application of the Er:YAG laser in dental caries removal and to present its advantages and limitations in clinical practice.

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Review Articles

2. METHODOLOGY

The article search for this literature review utilized the PubMed and Embase databases, and the selection included articles published between 2006 and 2021. The terms used were "Er:YAG laser" AND "dental caries removal". The inclusion criteria included articles in English published between 2006 and 2021 that evaluated the use of the Er:YAG laser to remove caries or related this type of laser to other methods. Articles that evaluated characteristics of the dental structure, or the influence of restorative materials after removal of caries with Er:YAG laser, were also considered. The search excluded: literature reviews, monographs, case reports, studies with bovine teeth, and studies with artificial or induced demineralization. The manual search included ten studies: three books, four original articles, and three reviews as they contained viable information to structure this literature review. Figure 1 shows the flowchart detailing the selection of articles. In total, this review included 39 references.

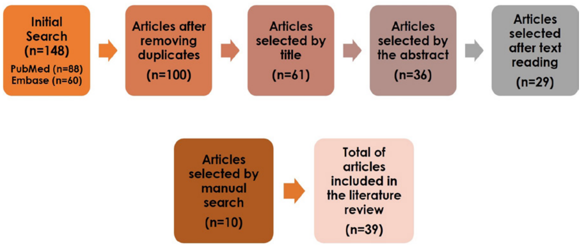

Figure 1. Flowchart of the article selection process.

3. LITERATURE REVIEW

Dental caries is described in the literature as a multifactorial disease influenced by genetic, environmental, and behavioral characteristics, being a complex disease resulting from the accumulation of specific acidogenic bacterial colonies present in the dental biofilm, capable of adhering to the tooth. These, in turn, produce acids from their metabolism using fermentable carbohydrates responsible for decreasing the pH on the dental surface, promoting the reduction of hydroxyapatite crystals and the widening of the intercrystalline spaces, leading to an increase in porosity and, consequently, the emergence of the disease [9].

Clinically, the active initial caries lesion appears on enamel as a white spot with a rough and opaque appearance. With the progression of demineralization, this lesion forms a cavity that can progress to reach the dentin, which then starts to show generally a yellow color, moist aspect, and softened consistency [9].

The removal of decayed enamel and dentin tissue requires the use of strong and sharp instruments to allow the proper preparation of the cavity. There are several instruments used for cavity preparation, such as hand instruments (chisels, dentin scoop) and rotary instruments (carbide burs with different types of active tip, diamond tips) [10]. Previous studies have shown that chemical-mechanical methods like Carisolv® and Papacarie® are also effective in removing caries [11,12].

The laser is another alternative that has been used in the dental field as an effective method for removing decayed tissue, being considered a conservative method since such removal is selective. Besides, laser treatment promotes greater comfort during the surgical procedure and without causing pulpal damage [13-15]. The type of laser most used for this purpose is the yttrium-aluminum-garnet erbium laser (Er:YAG).

The Er:YAG laser is excellent for the ablation of hard tissues, as it has a wavelength of 2.940nm, which is highly absorbed in water and hydroxyapatite. The erbium laser creates microexplosions in the hydroxyapatite by vaporizing the water molecules present in the hard tissues, which leads to the breakdown of this tissue during the ablation process. This laser operates in a pulsed mode, and the handpiece includes a spray of water to prevent tissue dryness and heat accumulation, allowing the energy to be absorbed efficiently. Thus, its action occurs without tissue carbonization and with minimal generation of heat [6]. Its use was approved for these purposes by the Food and Drug Administration (FDA) in May 1997 [14].

Research that used scanning electron microscopy (SEM) and thermographic study to evaluate the pulp temperature during the use of Er:YAG laser in deciduous and permanent teeth showed that in the same pulse of energy, ablation in dentin was more effective than in enamel and that ablation and caries removal values were significantly higher in primary teeth when comparing to permanent teeth, but without exceeding the temperature of 5.5°C [7].

Eberhard et al. (2008) analyzed extracted decayed permanent molars in which they were sectioned and treated with fluorescence-feedback controlled (FFC) Er:YAG laser or diamond tips. The use of the FCC Er:YAG laser at a threshold of 7U (units) resulted in less dentin loss when compared to the use of diamond tips [16].

A randomized clinical trial compared the efficacy of the fluorescence-controlled Er:YAG laser and the low-speed bur in removing decayed tissue in adults. The results showed that the use of the FCC laser at a threshold of 7 and 8U promotes the same effectiveness of the bur, presenting insignificant numbers of remaining bacteria [17].

One research evaluated different techniques for caries removal and found no selectivity for demineralized tissue using the Er:YAG laser. In this study, the laser showed significant variability in the results, where several samples remained with amounts of remaining caries and others had tooth structure removed in excess [18].

A study evaluating the rate of ablation and selectivity of healthy and demineralized enamel and dentin promoted by a 30W (watts) diode-pumped Er:YAG laser operating on a pulse of 20-30µs (microseconds)

showed that this laser has considerable potential for selective removal of dental caries [19].
Analysis of the removal of demineralized dentin using the FFC Er:YAG laser showed that dentin ablation occurred effectively at fluorescence control values between 6U and 7U when measured by microCT (computed microtomography). While at a value greater than 8U, the removal of decayed dentin was unsatisfactory [20].
Kornblit et al. (2008) evaluated the effectiveness of the Er:YAG laser in removing caries in deciduous and permanent molars and observed that ablation in areas infected by caries promoted maximum maintenance of the remaining structure. According to these authors, the laser provided decontamination of the affected area and improved retention of the composite resin to the surface prepared with laser, promoting better marginal enamel sealing [2].
Yonemoto et al. (2006) evaluated the DIAGNOdent® as a guide for caries removal using the Er:YAG laser. Values set at 11-20 were able to remove caries preserving the affected dentin in vitro [21].
An in vivo study used 120 primary teeth from children aged 5 to 9 years, divided into four groups: air rotor, Carisolv®, Papacarie®, and Er:YAG laser. The results were visually and tactile observed, besides having the values of the DIAGNOdent® pen and the FLACC scale (Face, Legs, Activity, Cry, Consolability) to measure pain during the procedure. Air rotor and laser were the most effective and efficient methods, and laser and chemical-mechanical methods were considered more comfortable [13].
Another in vivo study evaluated the FFC Er:YAG laser for caries removal in pediatric patients. S. mutans and or Lactobacilli were found in 33.33% of the lesions. In a total of 79 lesions, 14 contained S. mutans and 15 contained Lactobacilli. The average log of colony-forming units (CFU) per sample was 0 for S. mutans and Lactobacilli. The average time to perform the procedure was 2.3±1.2min. Regarding pain, 93.8% of children considered laser usage comfortable [15].
One research biochemically analyzed decayed and healthy teeth treated by the fluorescence-controlled Er:YAG laser, where a layer of dentin was removed from the bottom of the preparation to determine the presence of hydroxylysylpyridinoline (HP) and lysylpyridinoline (LP) collagen cross-links using high-performance liquid chromatography. 100% HP and LP were found in decayed dentin and 0.33% HP and 0.68% LP in healthy dentin. After caries removal, 0.84% HP and 1.26% LP were found at the 5U fluorescence-control threshold and 1.56% HP and 2.48% LP at 10U. The Er:YAG laser proved to be a viable method for removing the irreversibly denatured collagen present in decayed dentin [1].
Scanning electron microscope was used to investigate the morphological changes in the hard dental tissues after caries removal and cavity preparation using different methods: Er:YAG laser, Carisolv® gel, high-speed diamond burs, and low-speed micromotor steel burs. The dental surface after using the laser remained highly retentive, without smear layer residues and with the presence of exposed dentinal tubules. The samples treated with Carisolv® gel presented a rough retentive surface and some dentinal tubules obliterated by denatured collagen and surface contaminants; surfaces prepared with low and high-speed burs showed a thick smear layer and no micro retentions [22].
An in vitro study evaluated marginal microleakage of cavities restored with glass ionomer, comparing Er:YAG laser with Apacaries gel and atraumatic restorative technique (ART), and found a higher level of infiltration with the use of the laser to remove caries compared to the other methods [23].
Studies show that different techniques for removing decayed tissue influence the bond strength of adhesive systems [24-27]. The study of Yildiz et al. (2013) concluded that the chemical-mechanical method or use of burs at low rotation compared to the Er:YAG laser show better results in terms of bond strength for both self-etch and total-etch adhesives [27]. In another study, using a 2-step self-etch adhesive system, the dentin surface prepared by the Er:YAG laser showed lower micro-tensile bond strength (μTBS) values compared to healthy dentin [24]. In the study of Sattabanasuk et al. (2006), the bond strength values of a total-etch adhesive system were similar for the Er:YAG laser and steel bur [25].
Sirin Karaarslan et al. (2012) evaluated the micro-tensile bond strength of 3 types of adhesive systems - Clearfil® SE Bond (2-step self-etch), G-Bond® (single-step self-etch), and Adper® Single Bond 2 (2-step total-etch) after caries removal using a spherical steel bur at low-speed, Carisolv® gel or the Er:YAG laser. Based on the results, the techniques used to remove decayed tissue showed significant differences in bond strength between the adhesive systems. There was no significant difference in the bond strength of total-etch adhesive systems comparing laser and bur groups. Using the laser, Adper® Single Bond 2 was superior to the other adhesive systems, indicating that total-etch adhesives are the best option in this type of caries removal method [26].
The microhardness and chemical composition of dentin vary according to the applied caries removal method. The chemical-mechanical technique (Carisolv®) showed lower microhardness of the remaining dentin and a considerable number of samples with residual caries (20%) when compared to the carbide bur and the Er:YAG laser (both 5%). There was no significant difference in calcium and phosphorus rates of the three evaluated groups [28].
A comparative clinical study between the bur and the Er:YAG laser to remove caries from primary molars showed that the laser was less efficient than the bur to remove caries. Regarding effectiveness, the two treatments were similar to remove caries in the pulp wall, and the bur was better in the surrounding walls. The composite resin restorations for both groups remained satisfactory after one year of treatment [8].
A double-blind clinical study, performed in children aged 7-10 years, evaluated composite resin restorations in primary teeth performed after selective removal of necrotic dentin using an Er:YAG laser and a carbide bur. Adhesive restorations did not suffer laser interference, and the SEM analysis showed that laser group restorations showed a 10% gap in its extension, and the group treated with a bur showed

a 20% gap in the cavosurface margin after 12 months of follow-up [29].
A longitudinal clinical study with four years of follow-up evaluated the clinical longevity of composite resin restorations after selective caries removal in permanent molars using the Er:YAG laser or bur preparation with chlorhexidine as dentin biomodifier. The Er:YAG laser group biomodified with chlorhexidine presented a statistically significant difference for marginal adaptation criteria compared to the other groups; for secondary caries criteria and clinical and radiographic evaluation of pulp vitality, there was no statistically significant difference between the evaluated groups. The authors concluded that the method of caries removal and dentin biomodification did not influence the survival rate of composite resin restorations [30].
Prabhakar et al. (2018) evaluated morphological changes and the presence of bacterial deposits in primary decayed molars submitted to carious tissue removal by Carie-Care (chemical-mechanical method), Er:YAG laser, and tungsten carbide spherical bur. The results showed that the laser group was the most effective of the three, with fewer bacterial deposits and no smear layer formation [31].
A meta-analysis evaluated the Er:YAG laser to remove caries and for cavity preparation in children compared to the traditional mechanical method. This study evaluated seven randomized clinical trials and found that the laser requires more operative time but is less painful. There were no statistically significant differences between the two types of treatment concerning retention, marginal adaptation, and marginal discoloration of restorations [32].
A recent systematic review showed that the use of burs, chemomechanical method, and the Er:YAG laser are efficient for caries removal, reduction of bacteria in the tooth cavity, and do not compromise the clinical performance of restorations [33].
An in vitro study compared the FFC Er:YAG laser with the Er:YAG laser in three different pulses (super short, medium short, and short pulse) regarding the efficiency of removing cariogenic bacteria and carious dentin and dentin temperature during ablation. The results showed that no experimental group had bacterial contamination after treatment. In the groups with varied pulses of laser energy, the dentin temperature was significantly higher than the FFC laser [34].
A study that evaluated and compared the Er:YAG laser, the tungsten bur, and the polymer bur in caries removal showed no difference between the treatment time comparing the three methods. Histological analysis showed that all groups effectively removed the infected dentin and the laser group showed a regular 5μm thick layer of denatured collagen. The group treated by the tungsten bur presented a smear layer, and the polymer bur group showed an affected dentin surface layer [35].
Matsumoto et al. (2007) clinically evaluated the applicability of the Er:YAG laser on 95 decayed teeth from 45 patients. No adverse reactions and no or little pain were reported in most treated teeth (89.5%). Tooth preparation was successfully performed exclusively by laser in 94.7% of the cases, and the operative time was on average 49 seconds [36].

4. DISCUSSION

The Er:YAG laser to remove caries has been widely studied in recent years, showing that it is a safe and comfortable method for the patient, minimizing the use of local anesthesia and maintaining pulp vitality [2,7,13,17].
Studies comparing different methods of caries removal found that the Er:YAG laser, together with the chemical-mechanical method, provided greater comfort and satisfaction for both the operator and the patient as they were less traumatic [13]. According to a systematic review, chemomechanical methods are the best option for a minimally invasive treatment [33]. In an in vitro study, the hand excavator was the most effective technique to remove caries in deciduous teeth [37].
Comparing caries removal effectiveness (capacity) between laser and carbide bur at low rotation, the results of the two methods were similar for removing caries from the pulpal wall; the bur was more effective on the surrounding walls of primary molars [8]. Both techniques showed similar results regarding the presence of residual caries [28].
The adjusted value in lasers with fluorescence-feedback control influenced selectivity for carious tissue in the studies evaluated in this literature review. Schwass et al. (2013) showed that the Er:YAG laser with fluorescence control selected between 7U and 8U was effective for removing demineralized dentin [20], as well as studies by Dommisch et al. (2008) [17] and Eberhard et al. (2008) [16], where the Er:YAG laser with fluorescence control at levels of 7U and 8U promoted caries removal similar to that obtained with the conventional bur, generating greater comfort and wellness to the patient. The use of a laser with fluorescence control set to 9U and 10U did not remove all decayed tissue [17]. Contrasting these results, Neves et al. (2011) did not find selectivity when analyzing samples prepared with the FFC Er:YAG laser at the threshold of 7U, where some specimens were overprepared, and others continued with decayed tissue. In this study, the laser was the evaluated method that presented the least minimally invasive potential [18].
Regarding the morphological changes generated on the treated dental surface, the laser did not promote thermal damage and also left the surface highly retentive and without the presence of a smear layer; while the use of burs in both high and low rotation promoted surfaces with a thick smear layer and absence of microretentions; the use of polymer burs left an affected dentin layer [22,35].
Despite the advantages of using laser as a method of removing decayed tissue, clinical studies have

shown variation in clinical time, with laser consuming about 3x more time than the use of burs [17] with an average treatment duration of 2.3±1.2min [15]. Other studies have also shown a longer average treatment time with the use of laser, but with a minor difference: 110s [8] or 49s [36] for the Er:YAG laser and 55s [8] for the low-speed carbide bur. Another disadvantage found in one of the selected studies was the presence of marginal infiltration in decayed teeth ablated by laser and restored with glass ionomer [23].

The bond strength of adhesive systems influenced the method used to remove caries [26]. According to the results, the authors suggest choosing a conventional adhesive system after caries removal by the Er:YAG laser and a self-etch adhesive system after using a chemical-mechanical method. These results corroborate the study by Neves et al. (2011) that found lower micro-tensile bond strength using a 2-step self-etch adhesive after caries removal by the Er:YAG laser compared to the chemical-mechanical method and the use of conventional burs [24]. In another study, the use of a chemical-mechanical technique or usage of burs at low-speed compared to Er:YAG laser showed better results in terms of bond strength for both self-etch and total-etch adhesive systems [27]. Other studies showed that the Er:YAG does not influence the bond strength value of a total-etch adhesive system [25, 38]; however, the study of Sattabanasuk et al. (2006) showed higher bond strength values for Er:YAG laser compared to steel bur evaluating a self-etch adhesive system (Clearfil Protect Bond) [25].

A 12-month follow-up of a randomized clinical trial with a split-mouth design showed that teeth with decayed tissue removed by both laser and bur and restored with a 2-step total-etch adhesive system and composite resin maintained satisfactory restorative treatment [8]. In a double-blind clinical study, the restorations of the laser group showed a lower percentage of a gap than the group treated by bur in the analysis performed by SEM at the same follow-up time [29].

In a biochemical analysis of dentin collagen on decayed surfaces treated with erbium laser through SEM, the percentage of dehydrated collagen and decayed dentin reduced after laser treatment, becoming similar to healthy dentin [1]. In the study of Krause et al. (2008), 42.9% of the samples had bacterial residues, but in only 7.1%, the bacterial count was greater than 100 CFU (colony forming units) [15].

The pulp response to the application of external heat was evaluated in an in vivo study using rhesus monkeys [39]. The results showed that a temperature increase of 2.2°C does not cause pulp changes and that increase of 5.5°C allowed pulp repair for most specimens (75%). In several studies, the use of the Er:YAG laser has proven not to generate thermal damage to the dental structure, not exceeding the temperature increase above the threshold tolerated by the dental pulp [2,7,19,34].

Table 1 summarizes the 29 studies selected by Pubmed and Embase.

Author (Year)	Substrate	Type of study	Evaluated parameters	Er:YAG laser specifications	Conclusion
Al-Batayneh et al. (2014) [7]	Sound and carious enamel and dentin from 40 primary e 40 permanent extracted teeth	In vitro comparative study	- Laser ablation in sound enamel and dentin - Comparison between the Er:YAG laser and the rotary bur for carious removal - Surfaces changes through SEM	- Wavelength: 2.94µm - Pulse energy: 200mJ - Pulse duration: 250µs - Frequency: 10Hz - Power output: 6W	- Laser creates greater crater depths in dentin than enamel for both types of teeth - Laser is more efficient than the rotary bur to remove caries in primary teeth - There was no significant difference between both methods regarding permanent teeth - Dental ablation did not exceed 5.5°C - SEM: dentin ablation with no smear layer
Baraba et al. (2018) [34]	60 teeth with dentin caries and 12 teeth without caries lesion.	In vitro comparative study	Caries removal efficiency of the FFC Er:YAG laser and different pulses of the Er:YAG laser -PCR analysis -Thermal alterations	FCC laser: -Pulse energy: 350mJ (enamel) and 250mJ (dentin) -Pulse duration: 400µs -Frequency: 4Hz -Threshold: 7U Laser with different pulses: -Pulses: 50µs, 100µs, and 300µs -Pulse energy: 350mJ (enamel) and 250mJ (dentin) -Frequency: 10Hz -Non-contact mode -Distance: 7mm	-Ablated specimens were bacteria-free -All laser evaluated were efficient for caries removal -FCC laser group presented the lowest average temperature

Review Articles

Bohari et al. (2012) [13]	120 carious primary teeth from children aged 5 to 9	In vivo comparative study	-Efficiency, efficacy, and level of pain of 4 methods of caries removal: air rotor, Carisolv®, Papacarie®, and Er:YAG laser	- Wavelength: 2.94µm -Pulse energy: 200mJ -Frequency: 20Hz -Power output: 4W -Contact mode	-Air rotor and laser were faster and more efficient -Carisolv®, Papacarie®, and laser were less painful
Cardoso et al. (2020) [33]	Carious primary teeth	Systematic review	-Dental caries removal efficacy, treatment time, need of anesthesia, CFU count, restoration performance, and pain perception among conventional, chemomechanical, and laser methods.		-All methods are efficient in reducing CFU count and in removing caries -Chemomechanical methods showed to be the best option for minimally invasive treatments -Conventional methods promote faster treatment, and Er:YAG is faster than Carisolv® and Papacarie® -Chemomechanical and laser require less anesthesia and are also less painful -Restorations were not affected by any of the caries removal methods
Cebe et al. (2017) [38]	10 permanent molars with proximal caries	In vitro comparative study	- Microtensile strength of a total-etch adhesive system after caries removal by the Er:YAG laser and bur	- Wavelength: 2.94µm -Power output: 3.5W -Pulse duration: 300µs (short pulse mode) -Frequency: 10Hz -1mm distance -Energy density: 44J/cm²	-The Er:YAG laser did not impair the bond strength of a total-etch adhesive system
Celiberti et al. (2006) [37]	80 deciduous molars with dentin caries	In vitro comparative study	- Time and caries removal effectiveness and selectivity of carbide bur, Er:YAG laser, hand excavator, and polymer bur	- Wavelength: 2.94µm - Pulse energy: 200mJ - Frequency: 4Hz - Non-contact mode - Working distance: 12mm	- Carbide bur was the fastest and the Er:YAG laser the slowest technique - Polymer bur and laser left large amounts of underprepared areas - Carbide bur was the least conservative method - Hand excavator was the most effective technique to remove caries in deciduous teeth
Dommisch et al. (2008) [17]	102 teeth with active caries from 26 adult patients	Randomized clinical trial	- Efficiency, CFU count, level of pain between the FCC Er:YAG laser and carbide burss	- Wavelength: 2.94µm - Pulse energy: 250mJ - Frequency: 4Hz - Non-contact mode - Working distance: 10-20mm - Threshold: 7, 8, 9, and 10U	- FCC laser at the threshold of 7 and 8U and carbide burs showed similar results regarding S. mutans and Lactobacilli CFU - FCC laser was more comfortable but significantly more time consuming compared to carbide burs
Eberhard et al. (2008) [16]	165 permanent molars with dentin caries	In vitro comparative study	- Cavity extension after caries removal from 2 methods: bur and FCC laser in contact and non-contact mode	- Wavelength: 2.94µm - Pulse energy: 250mJ - Pulse repetition rate: 4 pulses/s - contact and non-contact mode - Working distance: 12-15mm - Threshold: 6, 7, and 8U	- the FCC Er:YAG laser was more conservative than the bur at a threshold of 7U - There was no difference between the laser in contact and non-contact mode
Jepsen et al. (2008) [1]	210 carious and 60 caries-free teeth	In vitro study	- Percentage of denatured collagen in dentin - Morphological aspects of dentin after laser ablation	- Wavelength: 2.94µm - Pulse energy: 250mJ - Pulse repetition rate: 4 pulses/s - non-contact mode - Working distance: adjusted by the pilot laser beam - Threshold: 5 and 10U	- the FCC Er:YAG laser showed less denatured collagen at a threshold of 5U - SEM analysis showed no smear layer and tubule exposure at the laser group and presence of smear layer and smear plug at the bur group - Transmission electron microscope (TEM) analysis showed no bacteria in the dentin surface after laser ablation

Juntavee et al. (2013) [23]	Primary second molars with occlusal caries	In vitro comparative study	- Influence of Apacaries gel, Er:YAG laser, and spoon excavator as caries removal methods in the marginal microleakage of glass ionomer restorations	- Pulse energy: 260mJ - Frequency: 30Hz - Pulse mode	- the Er:YAG laser promoted significant higher microleakage than Apacaries and spoon excavator in ionomer restorations
Katirci et al. (2016) [28]	Permanent molars with occlusal caries	In vitro comparative study	- Effectiveness of three caries removal methods by stereomicroscopic observations and microindentation hardness measurement - Chemical composition of the residual dentin	- Pulse energy: 250mJ - Frequency: 4Hz - Non-contact mode - Working distance: 10mm	- Carbide bur and Er:YAG laser had a similar outcome regarding caries removal - Carisolv® was less effective than the carbide bur and the Er:YAG laser and presented remaining dentin with a lower hardness compared to the other methods - There were no differences in the calcium and phosphate ratio among the three methods
Kornblit et al. (2008) [2]	30 carious teeth from children aged 4 to 12s	Clinical trial	- Possible postoperative complications after caries removal with the Er:YAG laser	- Wavelength: 2.94µm - Pulse duration: 140µs - Pulse energy: 120 to 200mJ - Frequency: 2 to 20Hz - focus mode - Working distance: 0.8 to 1cm	- Children treated with Er:YAG did not show any pain or sensitivity 7 and 28 days after the treatment
Krause et al. (2008) [15]	79 carious lesions from children aged 3 to 12	Clinical trial	- Efficacy of the FCC Er:YAG laser - CFU count after laser treatment - Children perceptions during treatment	- Wavelength: 2.94µm - Pulse duration: 400µs - Pulse energy: 250mJ - Frequency: 4Hz - non-contact mode - Working distance: 12cm - Threshold: 7U	- Treatment duration was 2.3±1.2 min - 93.8% of the children considered the laser treatment comfortable - After laser ablation, 42.9% of the samples showed residual bacteria; however, only 7.1% presented more than 100 CFU/sample
Li et al. (2019) [32]	Carious teeth from children	Meta-analysis	- Duration of treatment - Pain perception - Success of restorations		- Caries removal with laser is more time consuming than the use of bur - the Er:YAG laser is less painful than -the bur - There were no statistical differences in complete restoration retention, marginal discoloration, and marginal adaptation between Er:YAG laser and bur
Matsumoto et al. (2007) [36]	Carious teeth from adults	Clinical trial	- Pain, discomfort, assessment during cavity preparation, prognosis factor, and overall clinical evaluation	- Wavelength: 2.94µm - Pulse energy: 700mJ - Frequency: 8Hz	- Laser showed: low rate of pain during treatment, no discomfort, ample efficacy, substantial efficiency, good prognosis after three months of follow-up, and mean of treatment duration of 49s
Medioni et al. (2016) [35]	Carious molars and premolars	In vitro comparative study	- Effectiveness of - the Er:YAG laser, carbide bur, and polymer bur for caries removal	- Wavelength: 2.94µm - Pulse energy: 375mJ - Pulse duration: 50µs - Frequency: 10Hz - Quasi-contact mode	- Procedure time was similar for all the three methods - Histological analysis showed smear layer in the specimens treated with carbide bur, denatured collagen in the laser group, and a layer of affected dentin in the polymer bur group - All methods removed the infected dentin
Neves et al. (2011) [24]	Carious molarss	In vitro comparative study	- Influence of the 7 methods for caries removal in the bonding capacity of the remaining dentin	- Pulse energy: 250mJ - Pulse repetition rate: 4 pulses/s - Non-contact mode - Threshold: 7U	- Remaining denting from the FCC Er:YAG laser group showed lower µTBS values - Carisolv® showed the best results regarding µTBS, followed by carbide bur + caries detector

Review Articles

Neves et al. (2011) [18]	Carious molars	In vitro comparative study	- Caries removal effectiveness and minimally invasive potential of 9 methods for caries removal by microCT	- Pulse energy: 250mJ - Pulse repetition rate: 4 pulses/s - Non-contact mode - Threshold: 7U	- Chemomechanical methods + metal excavators showed the best results - the FCC Er:YAG laser showed the most variable results: specimens with over and others with under preparation - the FCC Er:YAG laser did not prove to be a selective method for caries removal
Polizeli et al. (2019) [29]	48 primary molars with occlusal and proximal caries from children aged 7 to 10	Double-blind, randomized clinical trial	- Salivary cortisol levels and clinical performance of restorations after caries removal by the Er:YAG laser compared to carbide bur	- Medium short pulse mode - Pulse energy: 250mJ - Frequency: 4Hz - non-contact mode - Working distance: 7cm	- Salivary cortisol levels were similar for laser and bur - There was no difference regarding marginal adaptation, retention, discoloration, and secondary caries for restorations from both groups after one year of follow-up
Prabhakar et al. (2018) [31]	Carious primary molars	In vitro comparative study	- Morphological changes -Bacterial deposits	- Wavelength: 2.94µm - Pulse energy: 200mJ - Energy density: 22.5J/cm² for 10 pulse/s - Non-contact mode	- the Er:YAG laser showed a minor quantity of bacterial deposits compared to Carie-Carie and carbide bur; Carie-Carie presented greatly bacterial deposits - Morphological changes: Carbide bur – thin smear layer and few open tubules; Er:YAG laser: irregular rugged surface, no smear layer, opened tubules; Carie-Carie – rough surface, smear layer, obliterated tubules
Sattabanasuk et al. (2006) [25]	Carious third molars	In vitro comparative study	- Influence of 3 methods for caries removal and two types of adhesive systems in the bonding capacity of the remaining dentin	- Pulse energy: 180mJ - Frequency: 2Hz - Non-contact mode	- The total-etch adhesive system (OptiBond Solo Plus) showed similar results in all groups (steel bur, laser, and SiC paper) - The self-etch adhesive system (Clearfil Protect Bond) showed lower bond strength in dentin treated with steel bur -Only the laser group showed similar bond strength for the two tested adhesive systems
Schwass et al. (2013) [20]	Teeth with proximal dentin caries	In vitro comparative study	- Different thresholds of FCC Er:YAG in the selectivity of caries removal	- Pulse energy: 600mJ (enamel) and 250mJ (dentin) - Frequency: 10Hz (enamel) and 4Hz (dentin) - Pulse duration: 400µs - Threshold: 4, 5, 6, 7, 8, 9, 10, 12, 16, and 20U - Non-contact mode	- Feedback control values higher than 8U did not remove infected caries efficiently - Threshold for conservative caries removal lies between 7 and 8U
Sirin Karaarslan et al. (2012) [26]	Carious molars	In vitro comparative study	- Influence of 3 methods for caries removal and three adhesive systems in the bonding capacity of the remaining dentin	- Wavelength: 2.94µm - Power output: 3.5W - Pulse duration: 300µs (short pulse mode) - Frequency: 10Hz - 1mm distance - Energy density: 44J/cm²	- The total-etch adhesive system: similar bond strength values for steel bur and laser and lower for Carisolv® - One-step and two-step self-etch adhesive systems: similar bond strength values for all three methods - the bur group: all adhesive systems had the same behavior - the laser group: total-etch adhesive showed the higher µTBS values - Carisolv®: two-step self-etch adhesive showed the best results

Tsanova & Tomov (2010) [22]	Carious teeth from adults	In vitro comparative study	- Ultrastructural changes in substrates treated with Er:YAG laser, Carisolv®, diamond bur, steel bur	- Pulse energy: 400mJ - Frequency: 20Hz - Power output: 8W	- Er:YAG laser: irregular and rough dentin surface with no smear layer, exposed tubules; retentive enamel - Carisolv®: dentin with rough and granular aspect, retentive surface The diamond bur: thin and smooth smear layer in most regions and absence in a few others, opened tubules The steel bur: smear layer and obliterated tubules
Valério et al. (2016) [8]	Carious primary molars from children aged 6 to 10	Split-mouth randomized clinical trial	- Er:YAG laser effectiveness compared to carbide bur - CFU count - Restoration longevity	- Pulse energy: 250mJ - Frequency: 4Hz - Non-contact mode - 7mm distance - Energy density: 39J/cm²	- The carbide bur is faster and more effective to remove caries in the surrounding walls than Er:YAG laser - CFU for S. mutans and Lactobacilli sp. was similar for both methods - One-year follow-up showed no differences in restoration longevity for both groups
Valério et al. (2020) [30]	Carious molars from children aged 8 to 12	Longitudinal clinical trial	- Influence of Er:YAG and carbide bur associated with chlorhexidine at the longevity of adhesive restorations after four years of follow-up	- Medium short pulse mode - Pulse energy: 260mJ - Frequency: 4Hz - Non-contact mode -12mm distance - Energy density: 41J/cm²	- The clinical longevity of the restorations was affected neither by the method for caries removal nor by the dentin biomodification with chlorhexidine at four years of follow-up
Yan et al. (2015) [19]	Teeth with occlusal caries	In vitro study	- Potential of a diode pumped solid-state (DPSS) Er:YAG laser for caries removal	- Pulse duration: 20-30µs - Frequency: 500Hz - Power output: 30W	- Ablation with minor thermal damage - Higher ablation rate in demineralized surfaces compared to the sound ones
Yildiz et al. (2013) [27]	Carious primary molar teeth	In vitro comparative study	- Influence of 3 methods for caries removal and two adhesive systems in the bonding capacity of the remaining dentin	- Wavelength: 2.94µm - Power output: 3.5W - Pulse duration: 300µs (short pulse mode) - Frequency: 10Hz - 1mm distance - Energy density: 44J/cm²	- Laser presented lower µTBS values than carbide bur and Carisolv® groups regardless of the adhesive system used (one-step self-etch and two-step total-etch) - Bur and Carisolv® presented the best results for both types of adhesive systems
Yonemoto et al. (2006) [21]	Molars with occlusal dentin caries	In vitro study	- Values of DIAGNOdent® that could be used as a guide for the removal of the outer layer of carious dentin with Er:YAG laser	- Pulse energy: 150-200mJ (enamel) and 50-150mJ (dentin) - Pulse duration: 200µs Frequency: 10, 20, 25 or 30Hz	- Laser + DIAGNOdent® values ≤10: overpreparation; laser + DIAGNOdent® values of 11-20: removal of the outer layer dentin; laser + DIAGNOdent® values of 21-30: partial removal of the outer layer dentin; however, there are some limitations for clinical application

Table 1. Summary of the selected articles.

5. CONCLUSION

The Er:YAG laser is a viable alternative for the treatment of caries since it can remove demineralized tissue without causing damage to the dental element, in addition to providing greater comfort for the patient due to the absence of noise, vibrations, and pressures during removal of decayed tissue and less need for anesthetic administration in most cases. Despite the advantages, its use requires more clinical time compared to the use of burs. Furthermore, the cost of the equipment, despite not having been addressed in the review, can also be considered a limiting factor. In general, the Er:YAG laser is as effective as the conventional and chemical-mechanical methods for selective caries removal.

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Review Articles

Questions

1. Which caries removal method is the least conservative?

❑a. Mechanical removal with dentin scoop;
❑b. Diamond tips and air rotor;
❑c. Er:YAG laser;
❑d. Use of a chemical-mechanical method.

2. Which is the Er:YAG laser wavelength?

❑a. 2.940nm;
❑b. 2.840nm;
❑c. 2.490nm;
❑d. 2.480nm.

3. Which sentence is correct?

❑a. Er:YAG is a selective method for caries removal;
❑b. Chemical-mechanical methods cause more pain for the patients;
❑c. Er:YAG can affect pulp vitality;
❑d. Carbide burs cannot be used in children.

4. In dentistry, which one is the most desirable phenomenon of the laser?

❑a. Diffusion;
❑b. Transmission;
❑c. Absorption;
❑d. Penetration.