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Application of lasers in periodontics: true innovation or myth?

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In the past 100 years there has been extensive development of the mechanical cutting devices used in dentistry. However, while considerable progress has been made in this area of mechanical cutting, dental patients are still afraid of the noise and vibration produced by the mechanical action of the air turbine or ultrasonic scalers. From the end of the 20th century until now, there has been a continuous upsurge in the development of laser-based dental devices based on photo-mechanical interactions. In fact, the French postal service recently released a memorial stamp showing the five greatest innovations of science in the 20th century. One of them was the laser. It has been nearly 50 years since the first laser device was produced in 1960 by Maiman (85). In the medical field, lasers have been successfully used since the mid-1960s for precise photocoagulation of the retina. Thus, ophthalmologists were the pioneers of laser application. Since then, lasers have been used in many industrial and scientific applications, which, in turn, has spurred new and innovative developments in this area.

The first report of laser application for the treatment of dental caries was published in *Nature* in 1964 by Goldman et al. (49). Since then, studies on the use of the neodymium-doped yttrium aluminium garnet (Nd:YAG) laser for caries prevention have been published by Yamamoto & Sato (182) and on the use of the carbon dioxide (CO_2) laser for dental caries treatment by Melcer et al. (90). The reported advantages of using lasers for treating dental caries are a reduction of the patient's physical and mental stress owing to low noise and little vibration, as well as improvement of operating conditions and outcomes as a result of the ablative, hemostatic and decontaminating effects of laser treatment.

However, it was found that those lasers designed for soft tissue removal were not suitable for the treatment of dental hard tissues. The Nd:YAG laser was not appropriate for dental caries treatment because of its difficulty in cutting hard tissues as well as its deeply penetrating effects causing potential pulpal damage (179). Cracking with fragmentation and carbonization of the cavity, in addition to melting and resolidification, were constantly observed in enamel and/or dentin as a result of use of the CO_2 laser. Thus, the first dental lasers approved by the US Food and Drug Administration, namely the CO_2, the Nd:YAG and the diode lasers, were accepted for use only for oral soft tissue procedures in periodontics. As periodontal tissues are composed of not only soft but also hard tissues, and the previous laser systems had not been shown to be effective for the treatment of hard tissues, a new laser system needed to be developed.

The lasers that show the most promise for hard tissue surgery are the erbium:YAG (Er:YAG) (2940 nm wavelength) and erbium, chromium: yttrium, scandium, gallium, garnet (Er,Cr:YSGG) (2790 nm) lasers. The absorbance of the Er:YAG laser in water is about 2.5-, 10- and 15,000-times higher than that of Er,Cr:YSGG, CO_2 and Nd:YAG lasers, respectively (51). As a result of the high absorption into water molecules, the erbium family of lasers has been shown to be capable of effectively ablating both soft and hard tissues without damaging deeper tissues (Fig. 1). In 1997, the Food and Drug Administration cleared the first Er:YAG laser system, then in use for preparing dental cavities, for incisions, excisions, vaporization, ablation and hemostasis of soft and hard tissues in the oral cavity. Because of the potential for possible soft and hard tissue applications, use of this laser has

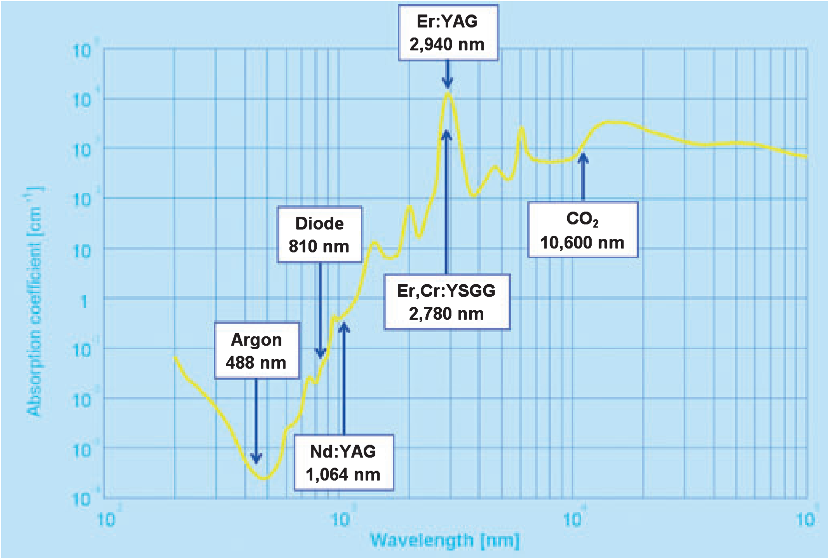

Fig. 1. Absorption spectrum for water of various lasers, such as Argon, Diode, neodymium-doped yttrium aluminium garnet (Nd:YAG), CO_2, Er,Cr:YSGG and erbium-doped yttrium aluminium garnet (Er:YAG). The Er:YAG laser has the best absorption coefficient of water among these laser systems. Data were calculated from Hale & Querry (51).

been investigated for scaling, root debridement and periodontal and peri-implant surgeries in periodontal therapy (57, 59).

What is a laser?

A laser is a device that produces coherent electromagnetic radiation. Laser radiation is characterized by a low divergence of the radiation beam and, with few exceptions, a well-defined wavelength. The term 'laser' is well known as the acronym for 'light amplification by stimulated emission of radiation'. The first letter in the acronym was supposed to change according to the type of radiation, and the term 'laser' was first reserved for visible light, but now it is used for any type of electromagnetic radiation produced in this way. Hence, we may say microwave laser (instead of maser), or infra-red laser (instead of iraser). In fact, most lasers intended for medical and dental use operate in the red to infra-red spectra of light.

Laser light is produced by pumping (energizing) a certain substance, or gain medium, within a resonating chamber (Fig. 2). The various laser systems are usually named after the ingredients of the gain medium, but three factors are important for the final characteristics of the laser light: composition of the gain medium, source of pump energy, and design of the resonating chamber. In addition, both the laser-delivery system (e.g. optical fiber or articulated arm with mirrors) and the application tip are of paramount importance clinically, as they may determine the ease of use, range of applications and energy efficiency of a laser system. Laser systems can be classified using many different criteria (Table 1). The most common classifications are those related to the type of gain medium and characteristics of the laser light.

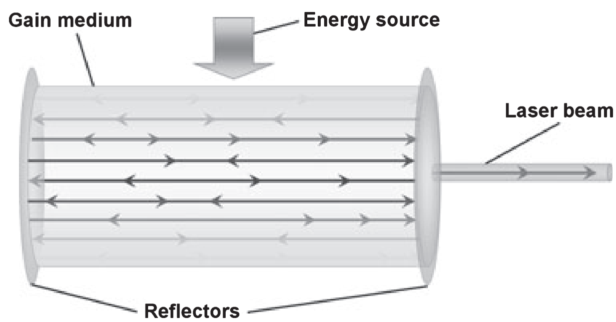

Fig. 2. Schematic drawing showing the main components of a laser. The gain medium is pumped by an external energy source. The gain medium then emits photons, which bounce back and forth between the reflectors. Part of the radiation is allowed to exit through an aperture in one of the reflectors, resulting in the laser beam.

When biological tissue is irradiated with laser light, four types of interactions may occur: reflection, scattering, absorption, or transmission. Basically, as the absorption increases, the reflection, scattering and transmission decrease. The type of interaction that predominantly takes place depends largely on the wavelength of the laser. For most biological tissues, higher absorption occurs in wavelengths with greater absorbance in water. The lasers with greater absorbance in water are the erbium lasers (Er:YAG and Er,Cr:YSGG) (Fig. 1). Erbium radiation is readily absorbed by most tissues, and this translates into less penetration and a shallower layer of laser-affected tissue.

Table 1. Classifications of laser systems

Criteria	Types	Examples*
Output energy	Low-output, soft, or therapeutic	Low-output diodes
	High-output, hard, or surgical	Diodes, CO_2, Nd:YAG, Er:YAG, Er,Cr:YSGG
State of the gain medium	Solid-state	Nd:YAG, Er:YAG, Er,Cr:YSGG, KTP
	Gas	HeNe, Argon, CO_2
	Excimer	F_2, ArF, KrCl, XeCl
	Diode	GaAlAs, InGaAs
Oscillation mode	Continuous-wave	CO_2, Diodes
	Pulsed-wave	CO_2, Diodes, Nd:YAG, Er:YAG, Er,Cr:YSGG, KTP

*Not an inclusive list.

What are the advantages and disadvantages of laser application in periodontal therapy?

Advantages of lasers

Because of the photo-physical characteristics of lasers, laser irradiation exhibits strong ablation, hemostasis, detoxification and bactericidal effects on the human body. These effects could be beneficial during periodontal treatment, especially for the fine cutting of soft tissue as well as in the debridement of diseased tissues. Thus, in periodontal therapy, laser treatment may serve as an alternative or adjunctive therapy to mechanical approaches. Previously introduced laser systems showed strong thermal side effects, causing melting, cracking and carbonization of hard tissues, such as root and bone. The recently developed Er:YAG and Er,Cr:YSGG lasers, however, can ablate both soft and hard tissues safely with water irrigation and are applicable to periodontal treatments such as scaling, debridement and bone surgery, and have minimal thermal effect. Thus, the erbium laser group has shown promise as a laser system for periodontal treatment approaches on hard tissues.

Disadvantages of lasers

First, the high financial cost of a laser apparatus is a significant barrier for laser utilization by periodontal practitioners. Second, each laser has different characteristics because of their different wavelengths. Thus, laser users should know the fundamental characteristics of each laser. However, only a few academic institutions provide proper and systematic education of the use of lasers in dentistry. For this reason, it is difficult for the users to learn all aspects of the techniques and precautions required for the newer technologies. Improper irradiation of teeth and periodontal pockets by lasers can damage the tooth and root surfaces as well as the attachment apparatus at the bottom of the pocket. Possible damage to the underlying bone and dental pulp should also be considered.

What are the risks and precautions in the clinical use of lasers?

Lasers may be a novel, effective tool for the treatment of periodontitis. However, lasers are completely different from conventional mechanical tools because lasers exert their effects not only in the contact mode but also in the noncontact mode. In addition, most lasers produce low to high thermogenesis during their interaction with the target tissues. The operator must be aware of the possible risks involved in clinical applications, and precaution must be exercised to minimize these risks when performing laser therapy (Table 2)(1, 9).

First, potential inadvertent irradiation to the patient's eyes, throat and delicate oral tissues outside the target site must be strictly prevented during treatment (1). The most important precaution in laser surgery is the use of glasses to protect the eyes of the patient, the operator and the assistants (1). In addition, accurate foot pedal control is necessary to ensure safe irradiation. Protection of the tissues surrounding the target is also recommended.

Second, thermogenesis during the interaction of the laser with the tissues must be addressed and well

Table 2. Risks and precautions in clinical use of lasers

1. Caution before and during irradiation
Use of glasses for eye protection (patient, operator and assistants)
Precautions for inadvertent irradiation and reflection from shiny metal surfaces
Protection of patient's throat and oral tissues outside the target site
Accurate foot pedal control
Adequate high speed evacuation to capture the laser plume
2. Risk of thermal injury during interaction with the tissues
Understanding of the penetration depth of each laser
Thermal injury to the root surface, gingival tissue, pulp and bone tissue
Effective use of water spray to minimize heat generation
3. Risk of excessive tissue destruction by direct ablation and thermal side effects
Excessive ablation of root surfaces and gingival tissue during pocket irradiation
Destruction of the attachment apparatus at the bottom of pockets during pocket irradiation
Bone and root surface alterations during gingival soft tissue surgery or pocket irradiation
Damage of the tooth enamel by inadvertent irradiation

controlled. With some lasers, such as the Nd:YAG and diode lasers, which exhibit deep-tissue penetration, thermal injury to the pulp tissue and underlying bone tissue is a concern during treatment. Also, a root surface that has received major thermal damage could render the tissue incompatible for cell attachment and healing. During treatment of hard tissue, the use of water spray minimizes heat generation by cooling the irradiated area and absorbing excessive laser energy (19, 171). Therefore, thermal injury must be prevented by using irradiation conditions and techniques that are appropriate for the wavelength of the lasers used.

Third, in periodontal applications, there exists the risk of excessive tissue destruction as a result of direct ablation and the possibility of thermal side effects in periodontal tissues during irradiation of periodontal pockets (9). Improper use of lasers could cause further destruction of the intact attachment apparatus at the bottom of the pocket wall as well as excessive ablation of root surfaces and the lining of the gingival crevice (9). Damage of the tooth surface should also be avoided during irradiation with CO_2 and Er:YAG lasers, as the enamel and dentin easily undergo melting, carbonization or ablation by these types of lasers.

Thus, in order to use lasers safely in clinical practice, the practitioner should have precise knowledge of the characteristics and effects of each laser system and their performance during application, and should exercise appropriate caution during their use.

Lasers versus conventional therapy

Soft tissue application

Gingival soft tissue procedures

Currently, lasers are generally accepted and widely used as a tool for soft tissue management (1, 23, 26). The major advantageous properties of lasers are relative ease of ablation of tissues together with effective hemostasis and bacterial killing. Gingivectomy, gingivoplasty and frenectomy are the most popular procedures carried out using lasers (112). Compared with the use of a conventional scalpel, lasers can cut, ablate and reshape the oral soft tissue more easily, with no or minimal bleeding and little pain as well as no or only a few sutures. Laser surgery occasionally requires no local anesthetic, or only a topical anesthetic (177). One animal study has reported that compared with conventional scalpel surgery, laser surgery produces less pain with the oral soft tissue incision (187). Little wound contraction and minimal scarring are other advantages of laser surgery that are not observed in scalpel surgery (84). Less postoperative pain in patients is also frequently observed by clinicians, but this has not yet been scientifically proven.

Use of electrosurgery also facilitates easy tissue incision accompanied with a strong hemostatic effect (163). However, the thermal effect of electrosurgery is relatively stronger, and the major concern is the potential risk of thermal damage to the underlying periosteum and alveolar bone by direct contact of the electrosurgical tip during gingival tissue management, leading to necrosis of bone or delayed wound healing (14, 153, 154). The pulpal pain experienced by the patient as a result of direct contact of the electrosurgical tip on the root surface during the procedure is also a concern when the local anesthesia is insufficient. Compared with electrosurgery, lasers have a higher comfort level in patients, resulting in less operative and postoperative pain and fewer complications. Thermal effects on the teeth and surrounding tissues are still a concern when using deeply penetrating types of lasers.

Thus, lasers are generally used for gingivectomy, gingivoplasty and frenectomy and for the removal of epulis or benign tumors, with some benefits when compared with the use of a scalpel or electrosurgery (112). Lasers are generally classified into two types, depending on their wavelength, as follows: types where the laser light penetrates the tissue more deeply (such as Nd:YAG and diode lasers), and types where the laser light is absorbed in the superficial layers (such as CO_2, Er:YAG and Er,Cr:YSGG lasers) (9). Depending on the penetration depth, the performance of each laser on soft tissue is different. With the CO_2 laser, the performance advantages are the rapid and simple vaporization of soft tissues with strong hemostasis, which produces a clear operating field and requires no suturing (113) (Fig. 3). Gingival hyperplasia is a typical indication for CO_2 laser treatment. The CO_2 laser is also effective in performing gingivoplasty for small tissue irregularities seen after periodontal and peri-implant surgery. The deeply penetrating lasers, such as the Nd:YAG and diode lasers, can be used to cut and reshape soft tissues (118, 177); however, these lasers have greater thermal effects, leaving a relatively thicker coagulation area on the treated surface than the lasers where the light is absorbed in the superficial layers of tissue (9). The surgical technique used with an Nd:YAG or diode laser is similar to that of electrosurgery. Only the Nd:YAG laser is contraindicated for the management of peri-implant soft tissue because this laser interacts readily with titanium that is found in most implants (119). The Er:YAG laser is also effective for soft tissue surgery. As this laser is the most highly absorbed in water among dental lasers (51), the width of the thermally affected layer after Er:YAG laser irradiation is minimal and reported to be approximately 10–50 μm in pig skin incisions (173). Therefore, the hemostatic effect is weaker than for other lasers, but the healing of the laser wound is relatively fast and comparable to that of a scalpel wound.

Esthetic gingival procedures

Lasers can be applied in esthetic procedures such as recontouring or reshaping of gingiva and in crown lengthening. With the use of some lasers, the depth and amount of soft tissue ablation is more precisely and delicately controlled than with mechanical instruments. In particular, the Er:YAG laser is very safe and useful for esthetic periodontal soft tissue management because this laser is capable of precisely ablating soft tissues using various fine contact

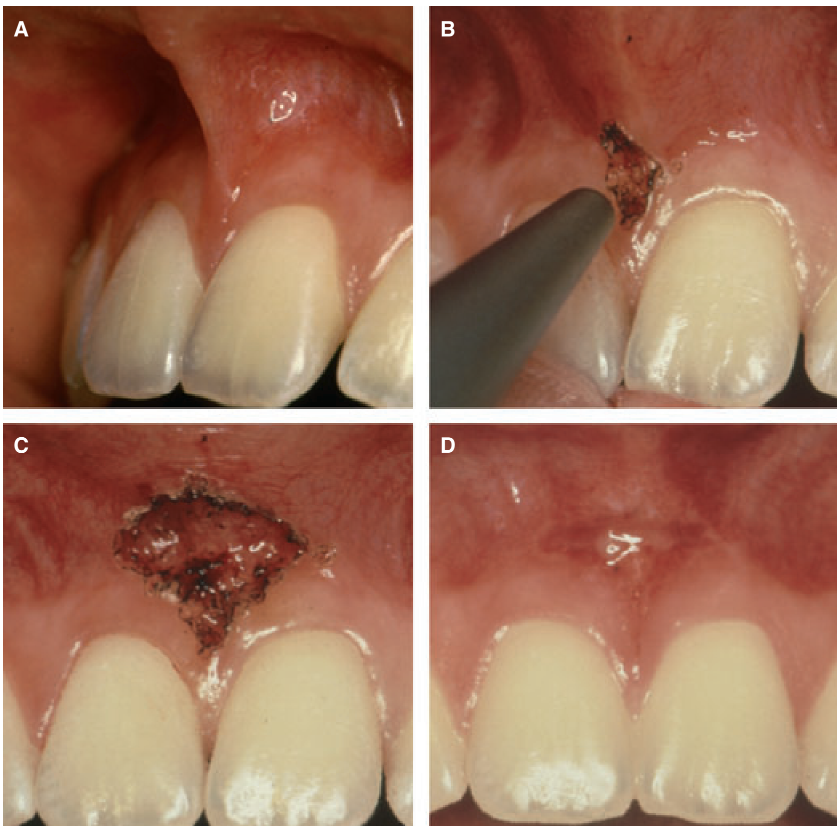

Fig. 3. Frenectomy using a CO_2 laser. (A) Before treatment: 16-year-old female subject. (B) The high attachment of frenum was easily ablated and resected with the continuous CO_2 laser at 4 W under local anesthesia in noncontact mode. (C) The laser-treated surface shows moderate carbonization but lacks bleeding as a result of the strong hemostatic effect of the CO_2 laser. No suturing was necessary after surgery. (D) The patient felt no postoperative pain and the wound healing was uneventful and favorable at 1 week. (case by: I. I.)

tips, and the wound healing is fast and favorable owing to the minimal thermal alteration of the treated surface (9, 58, 175).

Depigmentation is another indication for laser use in esthetic treatments. The CO_2, diode and Nd:YAG lasers can treat melanin pigmentation effectively (12, 100, 185). However, in areas of thin gingiva, these lasers have a risk of producing gingival ulceration and recession as a result of their relatively strong thermal and ⁄ or deeply penetrating effects (12). In these situations, the Er:YAG laser is more useful and safe for melanin depigmentation (7, 58) (Fig. 4). Following melanin depigmentation in dogs using the Er:YAG laser, the width of the thermally affected layer in gingival connective tissue has been reported to be approximately 5–20 μm (7). The ability of the Er:YAG laser to remove gingival melanin pigmentation has been reported in recent case reports, with esthetically significant improvement of gingival discoloration (121, 164). Furthermore, the application of the Er:YAG laser in combination with a surgical microscope makes the procedure more precise. The laser microsurgery approach facilitates the thorough detection and near-complete elimination of small areas of remaining pigmentation, as well as careful irradiation of the delicate area of the gingival margin and papilla. In addition, the Er:YAG laser can be utilized to remove metal tattoos (7, 58). The use of Er:YAG laser microsurgery enables effective and complete removal of the discolored gingival connective tissue, together with metal fragments, with minimum postoperative pain and little gingival recession, which cannot be achieved by conventional treatments (7, 58).

Fig. 4. Removal of gingival melanin hyperpigmentation using an Er:YAG laser. (A) Gingival tissue with a band of severe pigmentation before surgery in a 29-year-old man (former smoker). (B) Before treatment. (C) Er:YAG laser irradiation was performed at an energy output of 62 mJ ⁄ pulse (panel setting 80 mJ ⁄ pulse, ED 10 J ⁄ cm^2 ⁄ pulse) for the chisel tip and 45 mJ ⁄ pulse (panel setting 80 mJ ⁄ pulse, ED 15 J ⁄ cm^2 ⁄ pulse) for the curved tip and 30 Hz with water spray in contact mode under local anesthesia. The gingival epithelium containing pigmentation was easily and selectively removed by Er:YAG laser irradiation. No major thermal damage, such as carbonization, was observed. (D) Ten days after the procedure, the ablated area was covered with migrated epithelium. The patient had not felt any discomfort with the exception of slight pain on the day of treatment. (E) Eighteen months after the procedure, favorable wound healing was maintained without any gingival tissue defects or recession. The gingival color had a natural esthetic appearance (case by K. M.).

Summary

Soft tissue surgery is one of the major indications of lasers. The CO_2, Nd:YAG, diode, Er:YAG and Er,Cr:YSGG lasers are generally accepted as useful tools for this type of surgery. Laser surgery is superior to conventional mechanical surgery in that ablation, decontamination and hemostasis are easier to achieve, and there is potentially less operative and postoperative pain. However, possible damaging thermal effects to the underlying tissues should be kept in mind in the use of deeply penetrating lasers. For periodontal esthetic procedures, the Er:YAG laser is safe and effective as a result of its precise ablation with low thermal effect.

Nonsurgical pocket therapy

Basic studies

Conventional root debridement

In periodontal pockets, the exposed root surfaces are contaminated with an accumulation of plaque and calculus, as well as infiltration of bacterial endotoxins into the cementum. Usually, in the initial phase of periodontal therapy, debridement of the diseased root surface is nonsurgically treated by mechanical scaling and root planing, primarily by using manual or power-driven instruments. However, complete removal of bacterial deposits and their toxins from the root surface within the periodontal pockets is not always achieved with only the use of conventional mechanical therapy (3). In addition, access to areas such as furcations and grooves is limited owing to the complicated root anatomy. Furthermore, conventional mechanical debridement using curets is still technically demanding and time-consuming, and power scalers sometimes cause discomfort and stress in patients as a result of noise and vibration. Recently, the benefits of lasers, such as ablation, bactericidal and detoxification effects, as well as photo-biomodification, have been reported to be useful for periodontal pocket treatment, and the application of lasers has been suggested as an adjunctive or alternative tool to conventional periodontal mechanical therapy (9).

Removal of subgingival calculus

The CO_2 laser cannot be used for calculus removal because this laser readily causes melting and carbonization on the dental calculus (170). The Nd:YAG laser is also basically ineffective for calculus removal when a clinically suitable energy is employed (169). Unlike these lasers, the Er:YAG laser is capable of easily removing subgingival calculus without a major thermal change of the root surface *in vitro* (8–10) (Fig. 5). The level of calculus removal by this laser is similar to that of ultrasonic scaling, and the depth of cementum ablation has been reported generally to be 15–30 μm when the contact tip is applied obliquely to the root surface (9). Furthermore, Er:YAG laser treatment *in vivo* might provide selective subgingival calculus removal to a level equivalent to that provided by scaling and root planing (131, 139). Recently, a similar performance for calculus removal has been reported with the Er,Cr:YSGG laser (166). However, a lower degree of calculus removal with the Er:YAG laser than with scaling and root planing has also been noted in another *in vivo* study (38).

Regarding thermal generation, the deeply penetrating type of lasers, such as diode and Nd:YAG lasers, carry the risk of intrapulpal temperature elevations during laser irradiation on the root surface (178). With the Er:YAG laser, the use of water coolant can effectively prevent thermal generation during laser scaling while not compromising the efficiency of laser scaling (8, 10). A recent animal study showed that no adverse effects were observed histologically in the pulp tissue of roots following root debridement using an Er:YAG laser during flap surgery (94). Thus, the safety of Er:YAG laser subgingival scaling under water irrigation to the pulp tissue has been confirmed.

Interestingly, the frequency-doubled Alexandrite laser (wavelength 337 nm) is able to remove supragingival and subgingival calculus as well as dental plaque in a completely selective manner without ablating the underlying enamel or cementum (117). The unique properties of this laser seem useful; however, to date this laser is not available for general clinical use.

Root surface alterations

The CO_2 laser readily carbonizes the root cementum (127), and cyan-derived toxic products, such as cyanamide and cyanate ions, have been clearly detected on the carbonized layer by chemical analysis using Fourier transform infrared spectroscopy (157). The residual char layer has been demonstrated to inhibit periodontal soft tissue attachment *in vivo* (50), and thus focused CO_2 laser irradiation is contraindicated for root surface treatment.

Regarding the Nd:YAG laser, surface pitting and crater formation with charring, carbonization, melting and crater production have been reported after

Fig. 5. Nonsurgical periodontal pocket treatment using an Er:YAG laser or curet. The patient was a 62-year-old man suffering from generalized chronic periodontitis. The probing pocket depth was approximately 6 mm with bleeding on probing at the mesial-buccal site of the lower canines on both sides of the mandible and a large amount of subgingival calculus was noted before treatment (A and B). At the right mandibular canine, scaling and root planing, and ablation of pocket-inner epithelium were carried out by an Er:YAG laser at 35 mJ / pulse (panel setting 80 mJ / pulse, ED: 12.4 J / cm^2 / pulse) and 30 Hz in contact mode using a curved tip (0.6 mm diameter), under local anesthesia, while at the left canine scaling and root planing was performed as a control using a manual curet. Calculus removal was a little more difficult with the laser treatment than with the curet, but the laser completed the root debridement to the same degree as the curet (C). Lingual view immediately after laser treatment (D). Uneventful healing was observed 3 months following therapy in both laser-treated (E) and mechanically treated (F) sites. No complications or side effects were clinically observed. In both sites, the periodontal pockets werereduced to 2 mm without bleeding on probing, and 2 mm of clinical attachment gain was obtained (case by K. M.).

irradiation *in vivo*, even when irradiation was performed parallel to the tooth surface (97). Also, a decrease in the protein / mineral ratio and potential alteration of the surface by protein by-products, have been reported in Nd:YAG laser-treated cementum (156, 157). Although the Nd:YAG laser-treated root surface appears to be unfavorable for fibroblast attachment *in vitro* (168), the alterations of the irradiated surface are reversible, and additional root treatment, such as root planing or polishing, can restore the biocompatibility of the root surface (165). Regarding the diode laser, lasing dry or saline-moistened root specimens resulted in no detectable alterations. However, the blood-coated specimens showed severe damage, depending on the irradiating conditions (76).

In the case of the Er:YAG laser, several studies have described a characteristic morphological change of the root surface after irradiation. The Er:YAG laser-treated root surface under water coolant has been reported to have a micro-irregular appearance without cracks or thermal side effects, which are usually observed after treatment with a CO_2 or Nd:YAG laser (10). The superficial layer of the root surface ablated by Er:YAG laser irradiation presented a minimal affected layer with characteristic microstructure and staining (10, 27, 86) and without major compositional or chemically deleterious changes of the root cementum and dentin (127). With respect to the biocompatibility of the Er:YAG-lased root surface, the microstructured surface itself does not seems to be favorable for cell attachment (86). However, some studies demonstrate that when a suitable energy is selected, the root surface, after Er:YAG laser irradiation of the diseased surfaces, seems to offer better conditions for the adherence of fibroblasts *in vitro* than that after mechanical scaling alone (16, 40, 145).

Bactericidal and detoxification effects

Conventional methods for the treatment of periodontal disease are not completely effective in eliminating all types of bacteria. Although systemic and local administration of antibiotics into periodontal pockets is occasionally effective for disinfection, the frequent usage of antibiotics bears the potential risk of producing various resistant microorganisms. These limitations have led to a shift in emphasis from a purely mechanical approach to the use of novel technical modalities having additional bactericidal effects, such as lasers.

The defocus mode of the CO_2 laser has root conditioning effects, such as smear layer removal, decontamination (15, 25, 92) and the preparation of a surface favorable to fibroblast attachment (30). Regarding the Nd:YAG laser, several researchers reported a decontamination effect (176) and the inactivation of the endotoxins in the periodontally diseased root surface (45). The Er:YAG laser exhibits a high bactericidal effect against periodontopathic bacteria at a low energy level (6, 41), and this laser also has the potential to remove toxins diffused into the root cementum, such as bacterial lipopolysaccharides (181). The bacterial killing effect of argon laser radiation may be effective in the treatment of clinical infections caused by biofilm-associated species, such as *Prevotella* and *Porphyromonas* (54, 55).

Periodontal pocket treatment

One of the possible advantages of laser treatment of periodontal pockets is the debridement of the soft tissue wall. Conventional mechanical tools are not effective for the complete curettage of soft tissue. Gold & Vilardi reported the safe application of the Nd:YAG laser (1.25 and 1.75 W, 20 Hz) for removal of the pocket-lining epithelium in periodontal pockets without causing necrosis or carbonization of the underlying connective tissue *in vivo* (48). Recently, use of an Nd:YAG laser in a laser-assisted new attachment procedure has been advocated to remove the diseased soft tissue on the inner gingival surface of periodontal pockets (Food and Drug Administration 510 k clearance K030290). Quite recently, a case series by Yukna et al. (186) reported that the laser-assisted new attachment procedure could be associated with cementum-mediated new connective tissue attachment and apparent periodontal regeneration on previously diseased root surfaces in humans. Furthermore, in an animal study the Er:YAG laser also seems to induce new cementum formation after pocket irradiation (144). Thus, adjunctive or alternative use of laser treatment in periodontal pockets may promote more periodontal tissue regeneration than conventional mechanical treatment.

Clinical studies

The earliest clinical studies regarding the application of lasers in the nonsurgical pocket treatment of periodontitis began in the early 1990s using an Nd:YAG laser (Tables 3 and 4). The development of flexible optical fibers led to clinical applications of the laser in periodontal pockets. A high bactericidal effect of Nd:YAG laser irradiation in periodontal pockets was reported in some clinical studies (17, 24), but no differences in comparison to scaling and root planing were reported (116). In a double-blinded randomized clinical study, it was reported that the adjunctive application of Nd:YAG laser irradiation to conventional scaling and root planing resulted in significantly greater improvements in gingival index and bleeding on probing at specific time-points following therapy; however, differences in improvements of attachment level were not observed between groups (101). Furthermore, treatment with an Nd:YAG laser followed by scaling and root planing 6 weeks later seems to be more effective than scaling and root planing followed by laser therapy 6 weeks later in the improvements of clinical parameters. However, laser treatment alone was less effective than scaling and root planing alone for reducing interleukin-1β levels following therapy (83). On the other hand, clinical improvements following irradiation with the Nd:YAG laser alone were reported to be similar to those following ultrasonic scaling; significant decreases were observed, after therapy, in the amount of *Porphyromonas gingivalis* in subgingival plaque samples and in the volume of gingival crevicular fluid and amount of interleukin-1 in gingival crevicular fluid samples (93). In addition, greater pocket depth reduction and attachment gain, and reduction in the number of periodontopathic bacteria was demonstrated following Nd:YAG laser irradiation in combination with local minocycline administration compared with laser irradiation alone in the treatment of periodontitis (104).

Thus, studies examining the application of the Nd:YAG laser alone in the nonsurgical treatment of periodontal pockets have shown varying results, with

Table 3. *In vivo* studies on laser application in the treatment of periodontitis: removal of Plaque and Calculus and Effects on the Tooth Surface

Author and year (reference)	Laser	Laser parameters	Study design	Experimental group	Control group	Observation period	Findings
Non-surgical treatment							
Cobb et al. 1992 (24)	Nd:YAG	1.75–3.0 W, 20 Hz	Clinical (8 patients, 18 teeth)	Laser, Laser + RP, RP + Laser	Untreated	Immediately after treatment	Low effectiveness of laser for calculus removal, but decreased numbers of bacteria in laser-treated sites
Gold & Vilardi 1996 (48)	Nd:YAG	1.25, 1.75 W 62.5, 87.5 mJ / pulse 20 Hz	Clinical (6 patients, 24 teeth)	Laser		6 weeks	The complete removal of pocket lining epithelium without necrosis or carbonization of underlying connective tissue
Schwarz et al. 2001 (131)	Er:YAG	ED: 71, 83, 94 and 106 J / cm^2 / pulse*, 10 Hz	Clinical (40 teeth)	Laser		Immediately after (*in vivo* & *in vitro*)	Smooth root surface morphology after laser scaling *in vivo* not comparable to the marked morphological changes *in vitro*. The surface alterations were not related to the energy setting used
Schwarz et al. 2003 (139)	Diode	655 nm, 1.8 W ED: 0.63 J / mm^2 / pulse*	Clinical (24 teeth)	Laser	SRP with hand scaler	Immediately after (*in vivo* & *in vitro*)	Remaining debris and alternation of root surface such as grooves and cratering following laser irradiation
Schwarz et al. 2003 (139)	Er:YAG	ED: 19.4 J / cm^2 / pulse*, 10 Hz	Clinical (24 teeth)	Laser	SRP with hand scaler	Immediately after (*in vivo* & *in vitro*)	Selective subgingival calculus removal using a fluorescent calculus detection system. Smooth and homogeneous root surface morphology following laser treatment
Eberhard et al. 2003 (38)	Er:YAG	ED: 26 J / cm^2 / pulse*, 10 Hz	Clinical (12 patients, 30 teeth)	Laser	SRP with hand scaler	Immediately after	Lower effectiveness of laser for calculus removal but the obvious conservation of the underlying cementum in laser-treated sites
Crespi et al. 2006 (27)	CO_2	ED: 15 J / cm^2 / pulse*, 10 Hz	Clinical (15 patients, 40 teeth)	Laser	SRP with hand scaler	Immediately after	Clinical use of Er:YAG laser achieved plaque and calculus removal, providing a rough surface morphology
Schwarz et al. 2007 (144)	Er:YAG	ED: 10.2, 12.8, 15.4, 18.0 or 20.4 J / cm^2 / pulse, 10 Hz	Animal (5 dogs)	Laser	SRP with ultrasonic device	6 months	Significantly greater new cementum formation with inserting collagen type I fibers along the root surfaces in laser sites treated with higher ED than control sites
Yukna et al. 2007 (186)	Nd:YAG	3 W, 20 Hz	Clinical (6 patients, 12 teeth)	Laser	SRP with hand scaler	3 months	Connective tissue attachment and cementum formation in all laser-treated sites

Table 3. Continued

Author and year (reference)	Laser	Laser parameters	Study design	Experimental group	Control group	Observation period	Findings
Surgical treatment							
Williams et al. 1995 (180)	CO_2	ED: 41.28 J / cm^2 / pulse, 20 Hz	Animal (2 dogs)	Laser for degranulation	Manual curette	0, 3, 7, 14, 21 and 28 days	Mean times required for procedure in control sites were faster. Necrosed tissue or carbonized debris were phagocytosed
Centty et al. 1997 (22)	CO_2	8 W, 20 Hz	Clinical (5 patients)	OFD + laser irradiation to outer and inner aspects of mucoperiosteal flap	OFD	Biopsy during the surgery	Laser eliminated significantly more sulcular epithelium in comparison with conventional periodontal surgery
Crespi et al. 1997 (28)	CO_2	13 W, 40 Hz and 2 W, 1 Hz in defocus mode	Animal (6 dogs)	Laser for degranulation and root surface irradiation	GTR / SRP	6 months	Significantly greater formation of new periodontal ligament, cementum and bone in laser-treated sites
Gopin et al. 1997 (50)	CO_2	6 W, 20 Hz	Animal (2 dogs)	Laser, laser + RP for root surface treatment	Hand scaler and untreated	28 days	Inhibitation of periodontal tissue attachment to irradiated root surface by residual char
Mizutani et al. 2004 (94)	Er:YAG	ED: 18.8 or 14.5 J / cm^2 / pulse, 10 Hz	Animal (6 dogs)	Laser for degranulation and root debridement	Hand scaler	3 months	Significantly greater new bone formation in the laser group than the control group. Resorption of the affected layer on the lased bone and root surface during the healing process

ED, energy density; EMD, enamel matrix derivative; GTR, guided tissue regeneration; MWF, modified Widman flap surgery; OFD, open flap debridment; PD, pocket depth; RCT, randomized controlled trial; RP, root planing; SRP, scaling and root planing.
*Calculated from data presented in this review and / or data obtained during personal communication with the author.

Table 4. Clinical studies on laser application in non-surgical treatment of periodontitis

Author and year (reference)	Laser parameters	Study design	Experimental group	Control group	Observation period	Findings
Nd:YAG laser						
Radvar et al. 1996 (116)	0.5 or 0.8 W, 10 Hz	RCT (11 patients, 80 sites)	Laser alone at 0.5 and 0.8 W	SRP and untreated	6 weeks	No clinical or microbiological improvements on laser-treated sites
Ben Hatit et al. 1996 (17)	0.8–1.5 W, 8–15 Hz	RCT (14 patients, 150 sites)	SRP + Laser	SRP	Immediately after, 2, 6 and 10 weeks	Significantly reduced post-therapy levels of bacteria following adjunctive laser therapy
Neil & Mellonig 1997 (101)	2 W, 25 Hz	RCT, split-mouth design (10 patients, 186 teeth)	SRP + Laser	SRP and untreated	6 months	No significant difference in clinical improvements between SRP + laser therapy and SRP alone, but the laser-treated sites showed a tendency to improve steadily until 6 months post-therapy, different from the SRP alone group
Liu et al. 1999 (83)	3 W, 20 Hz	RCT, split-mouth design (8 patients, 52 sites)	Laser alone Laser + SRP 6 weeks later SRP + Laser 6 weeks later	SRP	12 weeks	Less effectiveness of laser treatment in comparison to SRP in reduction of interleukin-1β
Miyazaki et al. 2003 (93)	2 W 20 Hz	RCT (18 patients, 41 sites)	Laser	US	1, 4 and 12 weeks	Significant clinical improvements following laser and US therapies. Significant decrease of *P. gingivalis* and amount of interleukin-1 in the laser-treated sites, similar to the US sites
Noguchi et al. 2005 (104)	2 W, 10 Hz	RCT (16 patients, 135 sites)	Laser alone Laser + local minocycline Laser + povidone-iodine	Untreated	1 and 3 months	Greater reduction of bacteria on laser + minocycline sites than laser alone and sham-treatment sites
Diode laser						
Moritz et al. 1997 (96)	2.5 W, 50 Hz	Controlled study (50 patients)	SRP + Laser	SRP	1 and 2 weeks	Higher bacterial reduction in SRP + laser sites than SRP alone sites
Moritz et al. 1998 (95)	2.5 W, 50 Hz	RCT (50 patients)	SRP + Laser	SRP + H_2O_2 rinse	6 months	Significantly higher bacterial, BOP and PD reduction on laser-treated sites than SRP + H_2O_2 sites
Borrajo et al. 2004 (18)	2 W, pulsed	RCT (30 patients)	SRP + Laser	SRP alone	6 weeks	No additional improvements in adjunctive application of laser in comparison to SRP alone

Table 4. Continued

Author and year (reference)	Laser parameters	Study design	Experimental group	Control group	Observation period	Findings
Kreisler et al. 2005 (72)	1 W, CW	RCT, split-mouth design (25 patients)	SRP + Laser	SRP alone	3 months	Greater reduction of PD and increase of attachment gain in adjunctive application of laser in comparison to those of SRP alone
CO_2 laser						
Miyazaki et al. 2003 (93)	2 W, CW non-contact	RCT (18 patients, 41 sites)	Laser (irradiation to external surface)	US	1, 4 and 12 weeks	No decrease of *P. gingivalis* and amount of interleukin-1 following laser sites in comparison to the significant decrease in US sites
Er:YAG laser						
Watanabe et al. 1996 (175)	ED: 11.3 J / cm^2 / pulse,* 10 Hz	Case series (60 patients, 60 sites)	Laser		4 weeks	Safe and effective calculus removal and subsequent pocket depth reduction at 4 weeks
Schwarz et al. 2001 (132)	ED: 18.8 or 14.5 J / cm^2 / pulse,* 10 Hz	RCT, Split-mouth design (20 patients, 660 sites)	Laser	SRP	6 months	Clinical improvements following laser therapy were similar to or a little better than those of SRP therapy
Schwarz et al. 2003 (137)	ED: 18.8 or 14.5 J / cm^2 / pulse,* 10 Hz	RCT, split-mouth design (20 patients, 600 sites)	Laser + SRP	Laser	6 months	Additional SRP treatment following laser therapy did not improve and seems not necessary following laser therapy
Schwarz et al. 2003 (138)	ED: 18.8 or 14.5 J / cm^2 / pulse,* 10 Hz	RCT, split-mouth design (20 patients, 660 sites)	Laser	SRP	2 years	Clinical improvements following laser therapy could be maintained until 2 years
Sculean et al. 2004 (147)	ED: 18.8 or 14.5 J / cm^2 / pulse,* 10 Hz	RCT, split-mouth design (20 patients, 1306 sites)	Laser	US	6 months	Clinical improvements following laser therapy were similar to those of US treatment
Tomasi et al. 2006 (167)	ED: 18.8 J / cm^2 / pulse,* 10 Hz	RCT, split-mouth design (20 patients, 160 sites)	Laser	US	6 months	At 1 month following therapy, laser-treated sites showed significantly greater clinical improvements; however, similar results in comparison with US therapy was observed at 4 months post-therapy. No differences microbiologically were observed between laser and US treatments; however, faster healing and less discomfort during treatment were observed in the laser-treated group than in the US-treated group in the maintenance treatment

Table 4. Continued

Author and year (reference)	Laser parameters	Study design	Experimental group	Control group	Observation period	Findings
Crespi et al. 2007 (31)	ED: 16 J / cm^2 / pulse,* 10 Hz	RCT, split-mouth design (25 patients, 1200 sites)	Laser	US	2 years	Significantly greater clinical improvements of laser therapy than US therapy at 1 and 2 years post-therapy
Derdilopoulou et al. 2007 (36)	ED: 18.8 or 14.5 J / cm^2 / pulse,* 10 Hz	RCT (72 patients, 288 sites)	Laser	SRP, US and Sonic scaling	6 months	Lower bacterial reduction in laser-treated sites than in US sites. Also, US was more pleasant than laser therapy

BOP, bleeding on probing; CW, continuous wave; ED, energy density; NC, noncontact; PD, pocket depth; RCT, randomized clinical trial; SRP, scaling and root planing; US, ultrasonic scaling.
*Calculated from data presented in this review and / or data obtained by personal communication with the author.

the Nd:YAG laser generally showing less effectiveness for root debridement than conventional mechanical therapy. Considering the characteristics of the Nd:YAG laser as well as its clinical effects, it has been suggested that the Nd:YAG laser holds promise as an adjunctive therapy following conventional mechanical therapy in the nonsurgical treatment of periodontitis.

In the case of the CO_2 laser, because of the lack of an appropriate delivery system with suitable contact tips for periodontal pocket therapy, only a few clinical studies have been reported on the effects of this laser in the nonsurgical treatment of periodontitis (93, 99). Irradiation of the external surface of the marginal gingiva by a CO_2 laser (2W, CW) showed no changes in pocket levels of *P. gingivalis* and amount of interleukin-1 following therapy, which differ from the improvements reported following ultrasonic scaling (93). Also, CO_2 laser irradiation of the periodontal pocket using a special tip failed to result in a reduction of bacterial counts following treatment, and potentially damaged the soft tissue surrounding the periodontal pocket with cases of residual melted calculus being reported (99).

Studies evaluating the potential of the adjunctive application of a diode laser in the nonsurgical treatment of periodontitis have also recently been reported. Application of the diode laser has focused on the adjunctive use with mechanical debridement, with its potential to reduce or eliminate bacteria from periodontal pockets. The pulsed diode laser (805 nm) seems to produce a higher level of bacterial elimination from periodontal pockets than conventional scaling alone, especially with *Aggregatibacter actinomycetemcomitans* (96). In addition, the application of adjunctive-pulsed (95) or continuous-wave (72) diode laser irradiation after scaling showed significantly higher bacterial reduction and greater bleeding on probing improvements and reduction of pocket depth than scaling and root planing after 6 months of treatment. However, in another study, no further improvement was reported following scaling and root planing with adjunctive application of pulsed diode laser irradiation (18).

It has been proposed that the Er:YAG laser can be applied not only as adjunctive therapy, but also as an alternative to mechanical instruments for nonsurgical periodontal therapy. The favorable results of *in vitro* studies have led researchers to expect promising results from its clinical application. Following the first report by Watanabe et al. (175), which showed the safety and usefulness of Er:YAG laser therapy for subgingival calculus removal in nonsurgical pocket therapy, several randomized, controlled clinical studies reported the effectiveness of Er:YAG laser irradiation in comparison to conventional methods using hand curets or ultrasonic scalers. Although those studies showed improved clinical results following laser therapy, most failed to show consistently superior and / or additional benefits of the laser therapy. Schwarz et al. (132) reported that similar or better results were obtained following Er:YAG laser therapy than following conventional scaling and root planing therapy in terms of reduction of bleeding on probing, pocket depth and improvement of clinical attachment level, and that these clinical improvements could be maintained over a 2-year period (138). Additional scaling and root planing on the laser-treated sites seems to be unnecessary following laser therapy alone, because no additional improvement of clinical outcomes were reported in another study (137). Most recently it has been shown that Er:YAG laser therapy exhibited significant clinical improvements, 6 months following therapy, which were similar to those following use of the ultrasonic scaler alone (147). However, a recent clinical study demonstrated that treatment with the Er:YAG laser resulted in significantly higher pocket depth reduction and clinical attachment level gain at 2 years post-therapy in comparison to treatment with an ultrasonic scaler. One important finding of this study was that at 1 year post-treatment, there was increase of pocket depth and attachment loss in the ultrasonic group, whereas stability of Er:YAG laser-treated pockets with pocket depth ≥7 mm was noted until 2 years following treatment (31). Regarding bacterial reduction, in a recent clinical and microbiological study, no superior reduction in bacterial number was observed following treatment with the Er:YAG laser in comparison to ultrasonic scaling (36). When investigating patients' perceptions, ultrasonic scaling was more pleasant than therapy with an Er:YAG laser or hand curet instrument (36). Furthermore, in a study evaluating treatment of periodontal pockets using an Er:YAG laser in a periodontal maintenance program, no differences were reported in the microbial profiles between treatment with the Er:YAG laser and ultrasonic scaling, although faster healing (pocket depth reduction and clinical attachment level gain) and less discomfort during treatment were observed in the group treated with the Er:YAG laser (167).

Summary

Laser therapy, or laser-assisted pocket therapy, may be promising new approaches in periodontics. However, based on the results of previous studies, it appears at present that the CO_2 laser is not suitable for nonsurgical pocket applications because this laser is less effective for root debridement and has the potential to produce thermal damage in the periodontal pocket and surrounding tissues.

The application of Nd:YAG and diode lasers has been recommended for bacterial elimination as well as for soft tissue debridement within periodontal pockets as an adjunct in nonsurgical pocket therapy, in combination with mechanical instrumentation. This is because of the bactericidal and detoxification effects of these lasers in addition to their precise cutting ability for removal of the pocket-lining epithelium (48). Owing to the less effective removal of calculus as well as the considerable thermal damage that those lasers might produce on the root surface, these lasers cannot be used as a replacement for mechanical instruments in root debridement procedures.

The Er:YAG laser may hold the most promise for root surface debridement such as calculus removal and decontamination, as an adjunctive or alternative to mechanical debridement. However, from previously reported *in vivo* studies, there is no consensus regarding the levels of calculus removal and detection following application of the Er:YAG laser. The histological studies investigating periodontal attachment to laser-treated root surfaces are also inconclusive, although a few studies suggest the potential of laser treatment to promote new cementum formation (57, 144). The Er:YAG laser might be a potential approach to provide comprehensive treatment for both soft and hard tissues within periodontal pockets and intrabony defects. However, there are no clear trends that demonstrate superiority of the laser to conventional mechanical treatment.

Further clinical and histological studies evaluating periodontal healing following nonsurgical treatment of periodontal lesions using lasers need to be performed to assess the value of lasers in debridement of microbial deposits on root surfaces.

Surgical pocket therapy

In order for a periodontal surgical procedure to be successful with optimal tissue regeneration, it is necessary for the root surface and bone defect to be completely debrided and decontaminated. Laser application is effective in debriding areas of limited accessibility, such as deep intrabony defects and furcation areas where mechanical instruments cannot eliminate microbiological etiologic factors. Laser irradiation can facilitate complete debridement of the defect as a result of its ablation effect as well as improved accessibility when there is contact of the tip of the laser.

The focused CO_2 laser can easily achieve degranulation of bone defects. However, the laser irradiation produces carbonization on the bone and root surface (50, 180). On the other hand, the CO_2 laser, when used with relatively low energy output in a pulsed and ⁄ or defocused mode, may provide root conditioning, detoxification and bactericidal effects on the contaminated root surfaces. Crespi et al. (28) used the CO_2 laser in a defocused mode (13 W, 40 Hz) for the treatment of experimentally induced Class III furcation defects in dogs following flap surgery and reported that laser treatment promoted the formation of new periodontal ligament, cementum and bone. In addition, the CO_2 laser (8 W and 20 Hz) has been shown to increase the effectiveness of periodontal therapy through an epithelial exclusion technique in conjunction with conventional flap surgery procedures (22).

The Er:YAG laser has also been shown to be effective and easy to use for granulation tissue removal and root surface debridement during surgical procedures. In a study on dogs, Mizutani et al. demonstrated effective and safe granulation tissue removal and root debridement using an Er:YAG laser during flap surgery. Histologically, new bone formation was significantly more pronounced in the laser-treated group than in the curet-treated group after 12 weeks of healing (25) (Fig. 6). In clinical studies (Table 5), Sculean et al. (148) reported that application of the Er:YAG laser during the treatment of periodontal intrabony defects with access flap surgery is effective and safe with significant clinical improvements at six months following surgery, however, the laser treatment was equally effective as the mechanical debridement alone. In a recent study, Gaspirc et al. (46) reported the long-term clinical outcome comparing the Er:YAG laser-assisted periodontal flap surgery with conventional treatment using the modified Widman flap procedure. In this investigation, the reduction of pocket depth and the gain of clinical attachment level were significantly greater in the laser group at 6–36 months after surgery. Schwarz et al. (133) also confirmed that regeneration therapy using an enamel matrix protein derivative was equally effective on the root surface irradiated with an Er:YAG

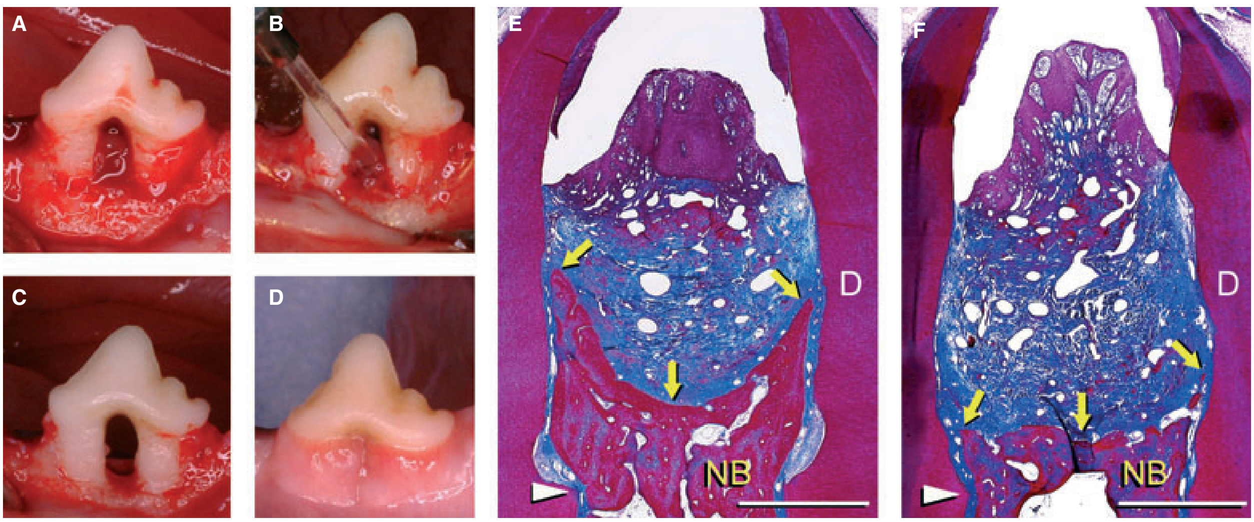

Fig. 6. Application of the Er:YAG laser in periodontal flap surgery in dog. Operative view of the periodontal flap surgery. After elevation of the mucoperiosteal flap (A), Er:YAG laser irradiation was carried out for degranulation and root debridement at 62 mJ ⁄ pulse (panel setting 95 mJ ⁄ pulse, ED 10.0 J ⁄ cm^2 ⁄ pulse) and 20 or 30 Hz using a chisel tip under sterile saline water spray (B). After debridement, no visible major thermal damage was observed on the laser-treated root and bone surfaces (C). At 12 weeks postsurgery, uneventful healing was observed in all sites (D). Histological photomicrographs of mesiodistal sections of periodontally treated furcation 12 weeks following surgery. In both laser-treated (E) and curet-treated (F) sites, periodontal tissue attachment with some degree of bone regeneration was observed. The newly formed bone (NB, arrows) was extended along the dental root surface (D) in the defect above the notch (arrowheads). Note the greater amount of new bone formation in the laser-treated site than in the curet-treated site. (Azan stain; bar, 800 μm; original magnification ×27). [Photographs from Mizutani K et al. Periodontal tissue healing following flap surgery using an Er:YAG laser in dogs. *Lasers Surg Med* 38: 314–324, 2006; with permission. *Lasers in Surgery and Medicine* © copyright (2006) John Wiley & Sons, Inc.].

Table 5. Clinical studies on laser application in the surgical treatment of periodontitis

Author and year (reference)	Laser parameters	Study design	Experimental group	Control group	Observation period	Findings
CO_2 laser						
Centty et al. 1997 (22)	8 W, 20 Hz	Randomized, controlled study, split-mouth design	OFD + laser irradiation to outer and inner aspects of mucoperio-steal flap	OFD	Biopsy during the surgery	Laser eliminated significantly more sulcular epithelium in comparison with conventional periodontal surgery
Er:YAG laser						
Schwarz et al. 2003 (133)	ED: 14.5 J / cm^2 / pulse, 10 Hz	Randomized, controlled study, split-mouth design	OFD + laser + EMD irradiation for degranulation and root debridement	OFD + EMD EDTA root conditioning	6 months	No significant difference in clinical improvements between EMD + laser therapy and EMD with EDTA root conditioning
Sculean et al. 2004 (148)	ED: 14.5 J / cm^2 / pulse, 10 Hz	Randomized, controlled study, split-mouth design	OFD + laser irradiation for degranulation and root debridement	OFD	6 months	No significant difference in clinical improvements between OFD + laser therapy and OFD using hand and ultrasonic instruments
Gaspirc et al. 2007 (46)	100, 140 or 180 mJ / pulse, 10 or 20 Hz	Randomized, controlled study, split-mouth design	MWF + laser irradiation to intrabony defect, root surface and flap	MWF	5 years	Adjunctive application of laser showed significantly greater reduction of PD and increase of attachment gain in comparison to MWF alone until 3 years after surgery

ED, energy density; EMD, enamel matrix derivative; MWF, modified Widman flap surgery; OFD, open flap debridement; PD, pocket depth.

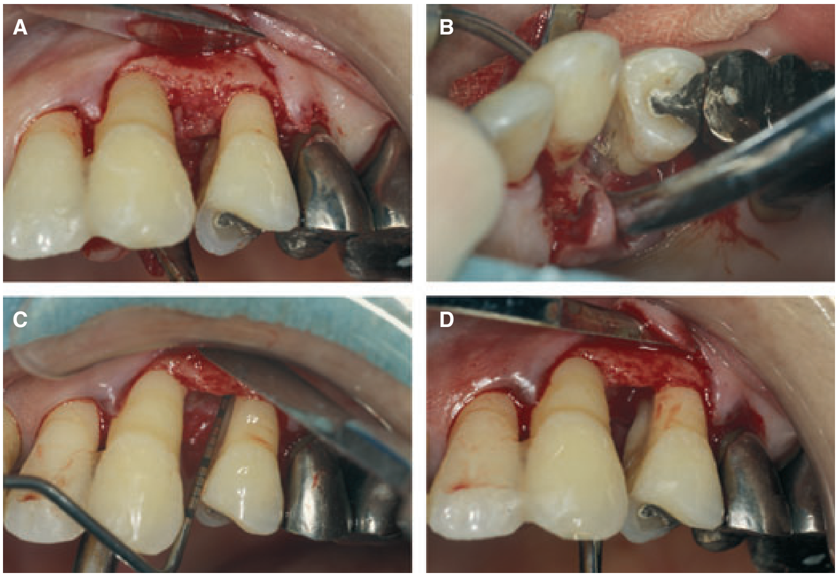

Fig. 7. Clinical application of Er:YAG laser in periodontal flap surgery. The patient was a 67-year-old woman. Following flap elevation (A), granulation tissue removal and root surface debridement including ablation of remaining subgingival calculus were performed at the mesial site of the maxillary left first premolar by the Er:YAG laser at 35 mJ ⁄ pulse (panel setting 80 mJ ⁄ pulse, ED: 12.4 J ⁄ cm^2 ⁄ pulse) and 30 Hz (80° curved tip) in contact mode under saline water spray (B). After complete degranulation, a two-wall, vertical bone defect was observed (C). Effective and safe debridement was performed without any visible major thermal damage, such as carbonization, on the laser-treated root and bone surfaces (D) (case by: A. A.).

laser when compared with the conventional procedure using enamel matrix protein derivate with ethylenediaminetetraacetic acid (EDTA) root conditioning. Therefore, application of the Er:YAG laser for surgical degranulation is a promising approach, and its effectiveness and safety have been demonstrated clinically (Figs 7 and 8).

Summary

During periodontal surgical procedures such as open flap debridement, laser application for removal of granulation tissue seems to be safe and effective with results equal to or even superior than those of conventional mechanical methods. Recently there has been a broader clinical use of lasers in flap surgery procedures. Further investigations are required to establish the reliability of this procedure using lasers and to clarify the additional benefits obtained by laser application.

Osseous surgery

Bone recontouring and reshaping are often part of periodontal surgical therapy to establish the physiologic anatomy of the alveolar bone and to allow for an optimal gingival contour after surgery. The most commonly employed conventional instruments for bone surgery are mechanical rotary instruments that use carbide or diamond burs, and hand instruments such as chisels and files. Sharp bone chisels are the instruments of choice, as these reportedly cause the least tissue damage and should be employed whenever access allows (56). Where access is limited, or where large amounts of bone must be removed, rotary instruments are indicated. Ultrasonic instruments have also been reported as an effective method for selective ablation of bone tissue (81, 129). In addition to these instruments, in recent years, the use of erbium lasers is becoming increasingly popular for bone surgery. Erbium lasers in general offer more precision and better access than mechanical instruments. They reduce the risk of collateral damage, particularly when compared with rotary instruments that may become entangled with soft tissues (such as with a reflected flap, for example). Lasers also improve the comfort of both patients and surgeons by markedly reducing the noise and eliminating the vibration associated with the mechanical cutting and grinding of bone tissue. In addition, the lack of vibration at the handpiece increases surgical precision. Nevertheless, despite the advantages of lasers over mechanical instruments, some issues still hinder a broader use of lasers in bone surgery. These include the reduced cutting efficiency of lasers compared

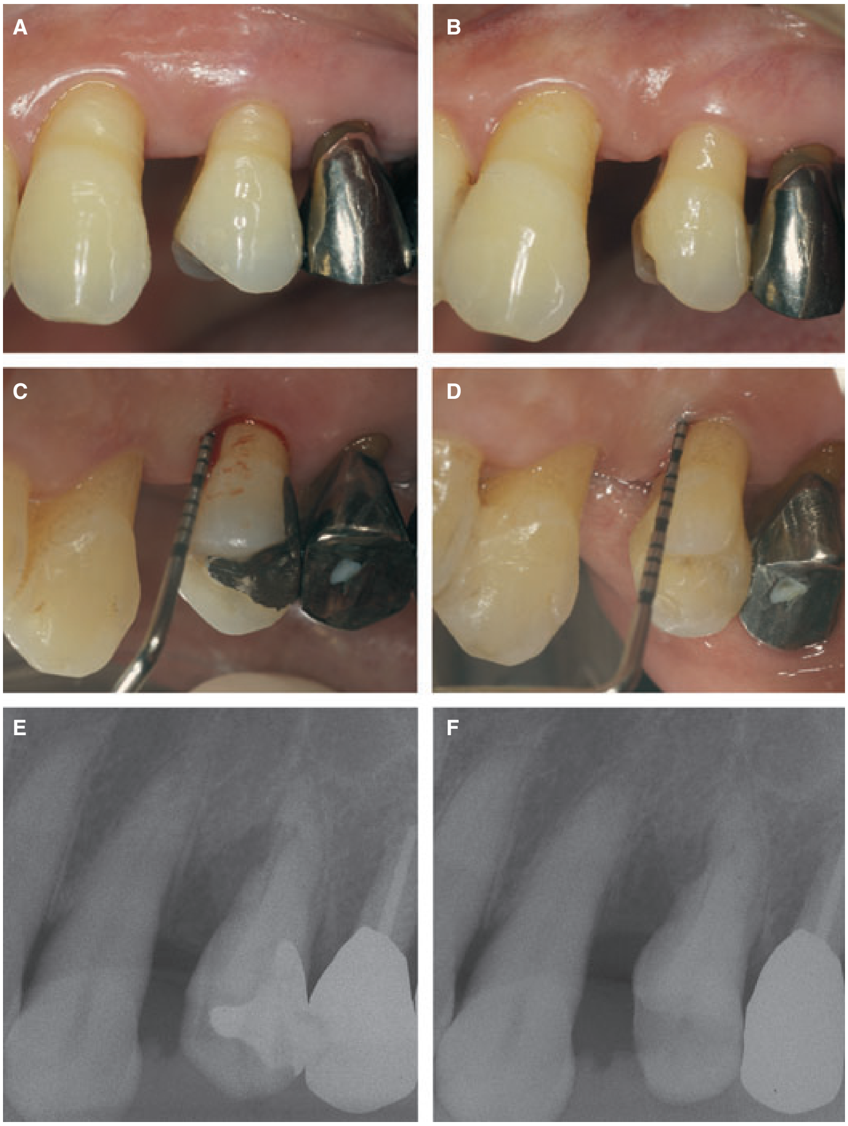

Fig. 8. Clinical and radiographic pictures of the Er:YAG laser-treated sites before (A and C) and after (B and D) the surgery shown in Fig. 7. Probing pocket depth before surgery at the linguo-mesial site of the upper-left premolar was approximately 7 mm with bleeding on probing (C) and decreased to 2 mm without bleeding on probing at 12 months following surgery (D). Although slight gingival recession was observed 12 months after surgery in comparison to before therapy, 4 mm of clinical attachment gain was obtained. No complications or side effects were clinically observed. The vertical bone defect observed before surgery on the mesial site (E) was repaired by bone regeneration following laser surgery. No adverse side effects were observed in the irradiated bone tissue (F) (case by: A. A.).

with mechanical instruments, lack of depth control and the effects of the laser on the surrounding irradiated tissue (Table 6).

Basic studies

Cutting efficiency

The ability of infrared lasers to cut bone tissue has been demonstrated (105). Nelson et al. (103) tested several energy levels and reported that the Er:YAG laser produced ablation of bone with minimal thermal damage to adjacent tissue, and that increasing the laser energy per pulse produced increasingly wider and deeper grooves. Studies using the Er:YAG laser suggest that depending on the size of the procedure and possibly on some irradiation parameters, laser ablation of bone is as efficient as bur drilling (110, 126). A recent report suggested that the cutting efficiency of bone can be greatly improved by using lasers of different wavelengths. In this experiment, the free-electron laser showed that, with all other parameters equal, wavelengths targeting the absorption by organic components of bone (6100 nm) greatly improved the cutting efficiency over the wavelength of the Er:YAG laser (2940 nm), which coincides with the peak absorption coefficient of water (184). Nevertheless, the currently available Er:YAG laser systems offer a cutting efficiency suitable for periodontal bone surgery, with greater precision when compared with mechanical rotary instruments.

Depth control

Rotary instruments only cut the tissue they come in contact with. Lasers, on the other hand, cut to an unknown depth away from the application tip. For

Table 6. *In vitro*, *in vivo* and clinical studies of laser application on bone tissue

Author and year (reference)	Type of study	Laser	Laser parameters	Purpose of application	Findings
Nelson et al. 1989 (102)	*In vivo* (rabbit)	Er:YAG	ED: 12.7 J / cm^2 / pulse, 10 Hz	Irradiated tissue characteristics	Er:YAG laser found useful as a cutting tool albeit with delay in healing
McKee et al. 1993 (88)	*In vivo* (rat)	CO_2	3, 7, 9 W, CW ED: 153, 357, 459 J / cm^2, respectively	Cutting efficiency and irradiated tissue characteristics	Novel alternative method for exposing unerupted dental tissues. Irradiated tissue presented densely packed or coagulated collagen fibrils and a separation of old bone and new bone
Lewandrowski et al. 1996 (82)	*In vivo* (rat)	Er:YAG	53 mJ / pulse, ED: 60 J / cm^2 / pulse, 1 Hz	Cutting efficiency and irradiated tissue characteristics	Comparable thermal damage in laser and mechanically cut bone. Satisfactory osteointegration of screws in holes made by the laser. Normal fracture healing
Krause et al. 1997 (69)	*In vivo* (rat)	CO_2	ED: 40 to 2062 J / cm^2	Irradiated tissue characteristics	Distinct layer of residual carbonized tissue and thermal necrosis
Friesen et al. 1999 (44)	*In vivo* (rat)	CO_2, Nd:YAG	CO_2: 8 W (1368 J / cm^2) Nd:YAG with coolant: (1368 J / cm^2) Nd:YAG without coolant: (571 J / cm^2)	Irradiated tissue characteristics	Delayed healing. Presence of residual char in the osseous defect. Beneficial effects of water coolant in regards to the healing response
Sasaki et al. 2002 (125)	*In vivo* (rat)	CO_2, Er:YAG	Er:YAG: 1 W (100 mJ / pulse, ED: 35.4 J / cm^2 / pulse,* 10 Hz), saline irrigation CO_2: 1 W, CW	Cutting efficiency and irradiated tissue characteristics	Er:YAG laser treatment resulted in tissue removal, absence of charring and presence of a characteristic tissue with two distinct sublayers: a superficial, greatly altered layer showing great amount of cracking and a deep, less affected layer with more discrete cracking. CO_2 laser treatment produced charring and almost no tissue removal
Sasaki et al. 2002 (126)	*In vivo* (rat)	CO_2, Er:YAG	Er:YAG: 1 W (100 mJ / pulse, ED: 35.4 J / cm^2 / pulse,* 10 Hz), saline irrigation CO_2: 1 W, CW	Irradiated tissue characteristics	Er:YAG laser produced a characteristic rough tissue and entrapment of fibrin, suggesting a suitable environment for the first events of bone healing. CO_2 laser produced melting and carbonization, and toxic substances that may jeopardize the healing process
Rupprecht et al. 2003 (122)	*In vivo* (rabbit and minipig)	Er:YAG	300–2000 mJ 1, 10, 15 and 20 Hz	Depth control	Highly selective ablation of bone when applied with a closed-loop control system

Table 6. Continued

Author and year (reference)	Type of study	Laser	Laser parameters	Purpose of application	Findings
Abu-Serriah et al. 2004 (2)	Clinical	Er:YAG	700 mJ, 10 Hz	Cutting efficiency	Er:YAG laser bone ablation was more time consuming than bur drilling
Pourzarandian et al. 2004 (114)	*In vivo* (rat)	CO_2, Er:YAG	Er:YAG: 1 W (100 mJ / pulse, ED: 35.4 J / cm2 / pulse,* 10 Hz), saline irrigation CO_2: 4 W, CW	Irradiated tissue characteristics	Er:YAG laser irradiation caused a faster initial bone healing. CO_2 laser irradiation produced thermal necrosis and residual char layer
Ivanenko et al. 2005 (60)	*In vivo* (dog)	CO_2	80 mJ / pulse	Cutting efficiency and irradiated tissue characteristics	Effective osteotomy was achieved with absence of tactile feedback, no aggravating thermal side effects and no healing delay. Healing process comprised a complete bony rearrangement of the osteotomy gap with newly built lamellar Haversian bone 22 days after laser surgery
Wang et al. 2005 (174)	*In vivo* (rabbit)	Er,Cr:YSGG	ED: 80 J / cm^2 / pulse, 20 Hz	Irradiated tissue characteristics	Er,Cr:YSGG laser cutting produced effective hemostasis, minimal delay of healing and minimal thermal damages to adjacent tissues
Mizutani et al. 2006 (94)	*In vivo* (dog)	Er:YAG	ED: 10.0 J / cm^2 / pulse, 20 and 30 Hz	Irradiated tissue characteristics	The affected layer produced by laser was scarcely detected in the bone tissue at 3 months postsurgery. Significantly more bone formation was seen in the laser-treated sites
Papadaki et al. 2007 (110)	*In vitro*	Er:YAG	ED: 63.6, 127, 191 and 255 J / cm^2	Cutting efficiency	Er:YAG laser osteotomies were shown as feasible. Bone cutting was smooth and caused no carbonization
Youn et al. 2007 (184)	*In vitro*	Free electron	ED: 21.2 and 42.4 J / cm^2 / pulse, 10 Hz	Cutting efficiency	Ablation efficiency was dependent on wavelength. The wavelength of 6.1 μm provided the highest ablation efficiency
Stubinger et al. 2007 (160)	Clinical	Er:YAG	ED: 64 or 177 J / cm^2 / pulse,* 12 Hz	Cutting efficiency and depth control	Laser osteotomies were efficient and precise, with satisfactory healing and no thermal damage, but the procedures were time consuming and offered no depth control
Stubinger et al. 2007 (161)	Clinical	Er:YAG	ED: 64 or 177 J / cm^2 / pulse,* 12 Hz	Cutting efficiency	Laser produced precise bone ablation without any visible negative thermal side effects, but the procedures were more time consuming

CW, continuous wave; ED, energy density.

*Calculated from data presented in this review and / or data obtained by personal communication with the author.

wavelengths well absorbed by biological tissue, such as CO_2 and the Er:YAG lasers, the ablation layer is shallow, but variable, according to the irradiation parameters and is therefore difficult to predict. On the other hand, lasers can be coupled with systems for monitoring tissue type, and in this case actually offer a significant advantage over mechanical instruments. One closed-loop tissue-monitoring system has been successfully adapted to an Er:YAG laser (122). In any case, depth control is rarely an issue during periodontal surgery, as damage to underlying tissues may be avoided by adjusting the angle of the laser application tip.

Characteristics of the irradiated bone

Concerns have been raised regarding the use of lasers in bone surgery as a result of the lack of information regarding the nature of the remaining irradiated tissue. This concern was backed by initial reports indicating unfavorable healing after laser-assisted bone surgery (4, 44, 88, 102). These unfavorable observations were based on experiments with a conventional CO_2 laser (4, 44, 88), or with an Er:YAG laser without saline irrigation (102). Previous reports showed that irradiation of bone with a CO_2 laser leads to severe carbonization and melting (125, 126). Fourier transform infrared spectra of bone surfaces showed that the extremely high temperatures produced by CO_2 laser irradiation cause denaturation of proteins and formation of toxic by-products (126). Likewise, Er:YAG laser irradiation of hard tissues without water coolant may result in superficial charring and the formation of toxic substances (127). Such toxic substances may delay the healing process (69, 157).

On the other hand, bone ablation by application of an Er:YAG laser with saline irrigation results in minimal thermal changes and no toxic substance production (126). One characteristic of the Er:YAG-lased bone tissue that must be considered is the thin af-

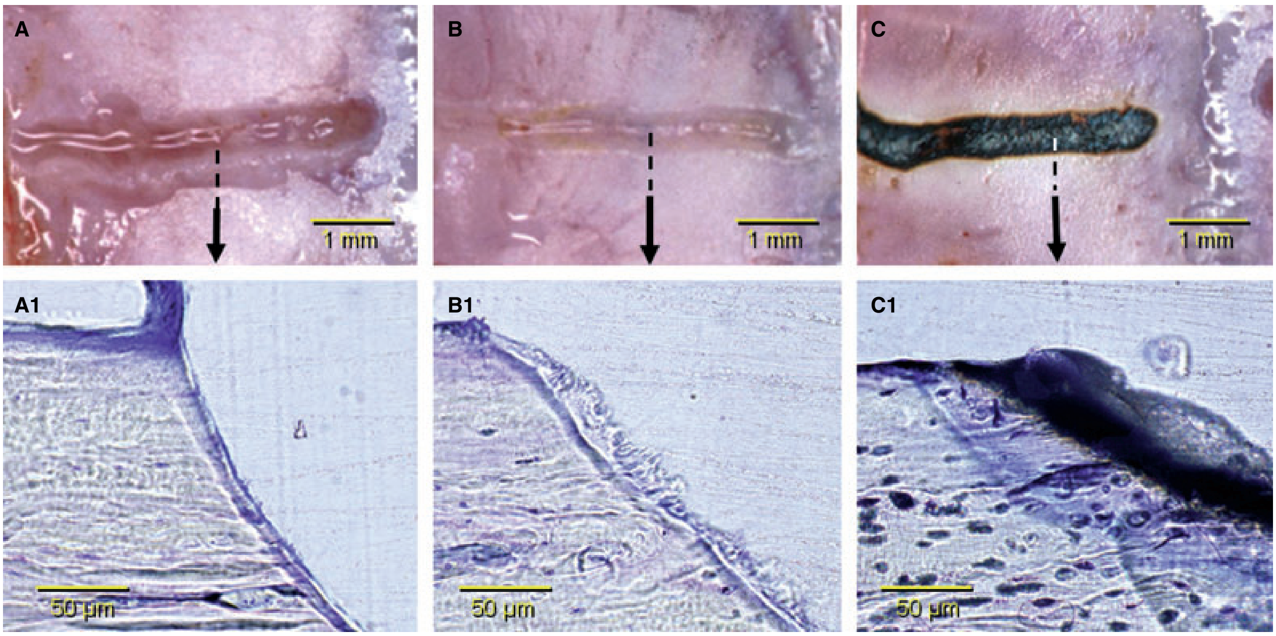

Fig. 9. Comparison of bone ablation by bur drilling, Er:YAG laser and CO_2 laser. Operative view of bone tissue after treatment by conventional drilling (A), Er:YAG laser (B) and CO_2 laser (C). A1, B1 and C1 are the respective photomicrographs of the nondecalcified histological sections. Bur drilling produced a groove accompanied by the soft tissue remnant on one edge. Irradiation with the Er:YAG laser also produced a groove with precise edges. Irradiation with the CO_2 laser resulted in a black carbonized line surrounded by whitish coagulation. Histologically, the Er:YAG-lased surface presented a thin affected layer with irregular borders. This layer exhibited a lightly stained superficial layer with no defined structures and a darkly stained underlying layer. The mean thickness of this layer ranged from 13.2 to 30 µm (mean 21.9 µm). The bur-treated surface was covered with a thin smear layer with a regular border. A darkly stained layer was detected beneath the thin smear layer. In the CO_2-lased specimen, the tissue removal was minimal. However, the surface showed major carbonization surrounded by an extensive, darkly stained layer at deeper sites. [Photographs from Sasaki, KM et al. Ultrastructural analysis of bone tissue irradiated by Er:YAG Laser. *Lasers Surg Med* 31: 322–332, 2002; with permission. *Lasers in Surgery and Medicine* © copyright (2002) John Wiley & Sons, Inc. and Sasaki, KM et al. Scanning electron microscopy and Fourier transformed infrared spectroscopy analysis of bone removal using Er:YAG and CO_2 lasers. *J Periodontol* 73: 643–652, 2002; with permission. *Journal of Periodontology* © copyright (2002) American Academy of Periodontology (adapted)].

fected layer of lased tissue that remains after irradiation. A morphological analysis of this layer showed that it contains irregularities that contribute to entrapment of the initial components of the early healing process (126) and therefore the lased bone heals more quickly compared with bone treated using conventional procedures (114). Recent reports indicate healing outcomes following laser treatment of bone that are comparable to or even better than those obtained after treatment of bone with mechanical tools (2, 60, 82, 114, 174). An animal study demonstrated that with the Er:YAG laser, debridement of bone defects with saline irrigation resulted in new bone formation with only minor histological alterations, suggesting resorption of the affected layer by bone remodeling during the wound-healing process (94). However, microfractures were detected within this affected layer, which might compromise the resistance of the junction between the lased bone tissue and the newly formed tissue, and ultimately jeopardize the integrity of the newly formed tissue (125) (Fig. 9). Therefore, the real benefits of the affected layer and strength supported by the new bone tissue have yet to be clarified.

Clinical studies

Recently, clinical applications for the Er:YAG laser in osseous surgery have been reported (2, 160, 161). Although in procedures involving large amounts of bone removal, the cutting efficiency of the Er:YAG laser has been reported to be lower than conventional drilling, Er:YAG laser irradiation with water cooling showed good clinical results with precise bone ablation without any visible, negative, thermal side effects impairing the wound healing for removal of impacted teeth and intra-oral bone grafting. However, the lack of depth control when cutting bone immediately above critical structures such as nerves or larger blood vessels, and longer treatment time of laser osteotomy, were deemed limitations to routine clinical application.

Summary

Although the use of lasers for bone surgery offers some advantages over conventional mechanical instruments, the concerns raised by some studies are still justifiable for the general practitioner. Currently, the Er:YAG laser is safe and useful for periodontal bone surgery in procedures such as osseous removal or recontouring, when used concomitantly with saline irrigation and when the resistance of the junction of newly formed bone over the lased bone at the treated surface is not a requirement.

Application of lasers in implant therapy

Basic studies

Dental implants have been widely used in clinical practice for the replacement of missing teeth in the rehabilitation of fully and partially edentulous patients, and have become an option in comprehensive periodontal treatment plans. Various lasers have been applied in the field of implant dentistry for uncovering the submerged implant (second-stage) prior to placement of the healing abutment. Use of lasers in these procedures may have several advantages, including improved hemostasis, production of a fine cutting surface with less patient discomfort during the postoperative period, and favorable and rapid healing following abutment placement, thus permitting a faster rehabilitative phase (11, 183). Furthermore, because of the ability of the laser to produce effective bone tissue ablation, some researchers have suggested using the Er:YAG laser to prepare fixture holes in the bone tissue in order to achieve faster osseointegration of the placed implants and to produce less tissue damage in comparison to conventional bur drilling (39, 63, 124, 142). Although these studies demonstrated uneventful wound healing of the laser-prepared fixture holes and effective osseointegration, the results are still controversial and there was no consensus regarding the superiority of the application of lasers. In most of these studies, no superior results were reported regarding the speed of osseointegration, with similar levels of wound healing in comparison with the bur-prepared sites (39, 124, 142). Also, the preparation time when using the Er:YAG laser was much longer than when using conventional drilling (142). However, Kesler et al. (63) reported a statistically significantly higher percentage of early bone-to-implant contact following use of the Er:YAG laser in comparison with the conventional methods. Thus, the favorable results of the application of lasers in the first- and second-stages of implant surgery suggest their potential in the field of implant dentistry. However, the use of lasers is generally limited to the second-stage soft-tissue procedures.

On the other hand, several researchers have recently investigated and proposed the application of lasers in the treatment of peri-implantitis. Although the monitoring of the implant condition and the further interception of peri-implant diseases by one strategy, the 'Cumulative Interceptive Supportive Therapy', was recently proposed, an ideal treatment protocol using optimal instruments has not yet been established (53, 67, 120, 130). Conventional mechanical instruments, such as steel curets or ultrasonic scalers, are not completely suitable for granulation tissue removal and implant surface debridement because they readily damage the implant titanium surfaces (42) and thus may interfere with the process of bone healing. Therefore, non-metal mechanical means for implant debridement, such as the use of plastic curets and carbon fiber curets, have been recommended (61, 135, 140, 141, 150). However, these methods are apparently ineffective for complete debridement of the bone defect as well as the contaminated implant surface (13, 61, 143, 146). Mechanical debridement around implants may also be difficult and time-consuming. Furthermore, implants with micro-structured surfaces have been recently clinically employed to improve anchorage to alveolar bone and to increase the bone-to-implant contact, resulting in better osseointegration (20, 21, 149). Accordingly, in the case of peri-implantitis, complete removal of contaminants such as bacteria and their products, and soft tissue cells from the rough surface, has become much more difficult when using mechanical debridement alone (61, 143, 146).

Therefore, the use of adjunctive chemical agents (such as irrigation or polishing with local disinfectants) and local or systemic antibiotic therapy have been performed with considerable success (120, 140, 141). However, the emergence of bacterial resistance to antibiotics, owing to frequent doses of antibiotics, is a matter of concern. In this context, there is significant interest in the development of an alternative antimicrobial treatment modality. Thus, a great deal of attention has recently been focused on novel therapeutic methods using lasers. Lasers were proposed for the treatment of peri-implant infections, based on their successful application with positive results as an adjunctive or alternative treatment for periodontal diseases. Lasers have been expected to resolve the difficulties and problems of conventional mechanical treatment. However, previous *in vitro* studies that examined the effects of laser irradiation on the implant surface and the adjacent bone tissue demonstrated that some types of lasers are unsuitable for peri-implant treatment (71, 98, 106, 119) (Table 7). Some studies demonstrated that the Nd:YAG laser is contraindicated for use in the treatment of peri-implantitis because irradiation using this laser readily produced morphological changes such as melting, cracks and crater formation of the titanium surface (71, 119), although a recent report showed its bactericidal effect with no damage to the titanium surface at low pulse energy (47).

With the CO_2 laser, no morphological changes are observed on the implant surface. In addition, irradiation of titanium surfaces with the CO_2 laser does not influence osteoblast attachment (29, 62). Therefore, this laser is commonly applied for decontamination of implant surfaces (29, 35, 62). The CO_2 laser is reported to be safe and to possess an ability to enhance bone regeneration when utilized for decontamination of implants in the treatment of experimentally induced peri-implantitis (159) and when clinically applied with beta-tricalcium phosphate in the treatment of peri-implantitis (34). However, previous studies also indicate that there is a risk associated with the high temperature elevation of the titanium implant surface and carbonization of the adjacent bone tissue during irradiation with the CO_2 laser (75, 98, 106).

Regarding the application of semiconductor lasers, it has been reported that no damage is observed on the titanium surface following irradiation with a diode laser and that this laser is capable of decontaminating rough implant surfaces (71, 119). However, there is a risk of heat generation on the peri-implant bone when improper irradiation parameters and techniques are followed, and the bactericidal effect of treatment with a diode laser is reportedly less effective than that of conventional methods using chlorhexidine (78).

It should be pointed out that in the treatment of peri-implantitis, not only decontamination of the implant surface, but also removal of the diseased granulation tissue around implants is necessary. Among the lasers applied in dentistry, the Er:YAG laser is considered to possess the best property for both degranulation and implant surface decontamination as a result of its dual actions of both soft and hard tissue ablation without causing thermal damage of the adjacent tissue.

Irradiation using the Er:YAG laser at appropriate energy settings seems to cause no change to the titanium surface (87, 136), and the irradiated titanium surface appears not to influence the attachment rate of osteoblasts on its surface (136). However, irradiation at high energy outputs may cause distinct surface changes of titanium (87). Irradiation using the Er:YAG laser facilitates effective removal of calculus

Table 7. *In vivo* and clinical studies on laser application in treatment of peri-implantitis

Author and year (reference)	Type of study	Laser type	Laser parameters	Purpose of application	Findings
Nonsurgical therapy					
Schwarz et al. 2005 (140)	Clinical	Er:YAG	ED: 12.7 J / cm^2 / pulse,* 10 Hz	Pocket debridement and decontamination	Clinical improvements at laser-treated sites after 6 months of therapy were similar to those at sites receiving conventional mechanical therapy
Schwarz et al. 2006 (135)	Clinical and histological	Er:YAG	ED: 12.7 J / cm^2 / pulse,* 10 Hz	Pocket debridement and decontamination	Clinical improvements at laser-treated sites after 24 months of therapy were similar to those of conventional mechanical therapy sites. However, a mixed chronic inflammatory cell infiltrate was found in histological observations
Schwarz et al. 2006 (134)	Clinical	Er:YAG	ED: 12.7 J / cm^2 / pulse,* 10 Hz	Pocket debridement and decontamination	Clinical improvements at 6 months of therapy, but between 6 and 12 months after therapy increases were observed in mean BOP score. In addition, loss of mean CAL between 6 and 12 months post-treatment was observed in both l aser and conventional mechanical therapy
Surgical therapy					
Deppe et al. 2001 (35)	*In vivo*	CO_2	2.5 W, CW	Decontamination	CO_2 laser irradiation is safe and effective for decontamination of peri-implant defects, showing significantly greater bone-to-implant contact than in the conventionally treated group
Stübinger et al. 2005 (158)	*In vivo*	CO_2	2.5 W, CW	Decontamination	Enhanced regeneration of bone in the CO_2 laser-treated sites
Deppe et al. 2007 (34)	Clinical	CO_2	2.5 W, CW	Decontamination	Safety and efficacy of CO_2 laser when applied with β-TCP

Table 7. Continued

Author and year (reference)	Type of study	Laser type	Laser parameters	Purpose of application	Findings
Schwarz et al. 2006 (145)	*In vivo*	Er:YAG	ED: 12.7 J / cm^2 / pulse,* 10 Hz	Granulation tissue removal and decontamination	Laser treatment seems to be more suitable for promoting re-osseointegration than plastic curet instrumentation plus antibiotics and ultrasonic scalers
Takasaki et al. 2007 (162)	*In vivo*	Er:YAG	ED: 10.0 J / cm^2 / pulse,* 10 Hz	Granulation tissue removal and decontamination	Degranulation and implant surface debridement were easier to perform using an Er:YAG laser than a plastic curet instrument. Histologically, the newly formed bone was more coronally positioned on the laser-treated implant surface

b-TCP, beta-tricalcium phosphate; BOP, bleeding on probing; CAL, clinical attachment level; CW, continuous wave; ED, energy density.
*Calculated from data presented in this review and / or data obtained by personal communication with the author.

and plaque from contaminated abutments and biofilms grown on sand-blasted and acid-etched titanium surfaces (87, 146). Furthermore, a high bactericidal potential on the implant with different surface characteristics, even at low energy densities, is obtained following Er:YAG laser irradiation (77). Decontamination of the titanium surface by Er:YAG laser therapy *in vitro* has been reported to be more effective than application of plastic curettes with adjunctive rinsing with chlorhexidine digluconate or an ultrasonic system (146). A recent study demonstrated that treatment of *P. gingivalis*-contaminated sand-blasted and acid-etched titanium implant surfaces using Er:YAG laser irradiation is capable of producing attachment of osteoblast cells. This is in contrast to observations of the nonlaser-treated control in which no further attachment of osteoblast cells was observed (43). In another study, it was reported that Er:YAG laser-irradiation treatment of *P. gingivalis*-contaminated rough titanium surfaces resulted in similar fibroblast proliferation on the implant surfaces when compared with sterile specimens and greater fibroblast proliferation when compared with untreated contaminated specimens (79). In addition, no temperature elevations at the implant–bone interface during implant surface decontamination with the use of the Er:YAG laser *in vivo* was reported (70).

In vivo and clinical studies

Recently, studies on the application of the Er:YAG laser for the nonsurgical treatment of peri-implantitis have been conducted (134, 135, 140). Schwarz et al. (140) demonstrated that Er:YAG laser treatment led to significant clinical improvements 6 months after therapy at the same levels as conventional mechanical debridement using plastic curets. The reduction of bleeding on probing was significantly higher in the Er:YAG laser-treatment group. However, more recently, increased mean bleeding on probing scores and loss of mean clinical attachment level between 6 and 12 months post-treatment in both laser and conventional mechanical nonsurgical treatment was reported, indicating poor peri-implant stability of both laser-treated and conventionally treated sites (134). In another long-term clinical study, Schwarz et al. reported that although clinical improvements were achieved following 24 months of healing, histopathological examination revealed the presence of a mixed chronic inflammatory cell infiltrate in the connective tissue stroma (135). Thus, it seems that nonsurgical therapy is not sufficient for complete healing of peri-implantitis sites (135). This indicates that surgical approaches are rather necessary in the treatment of peri-implant lesions.

In a recent animal study for the treatment of peri-implantitis in a circumferential crater-like bone defect, Schwarz et al. (141) reported that the application of Er:YAG laser irradiation during flap surgery resulted in improvements in all investigated parameters, and that laser treatment seemed to be more suitable for promoting re-osseointegration when compared with plastic curet instrumentation followed by subgingival application of an antibiotic agent and ultrasonic debridement. However, no significant differences in the bone-to-implant contact between both laser treatment and plastic curet instrumentation were observed. Most recently, Takasaki et al. (162), demonstrated safe and effective application of Er:YAG laser irradiation for degranulation and implant surface debridement in the treatment of experimentally induced peri-implant infections in dehiscence-type defects in dogs. Degranulation and implant surface debridement was easier to perform using Er:YAG laser irradiation than using plastic curet instrumentation (Fig. 10).

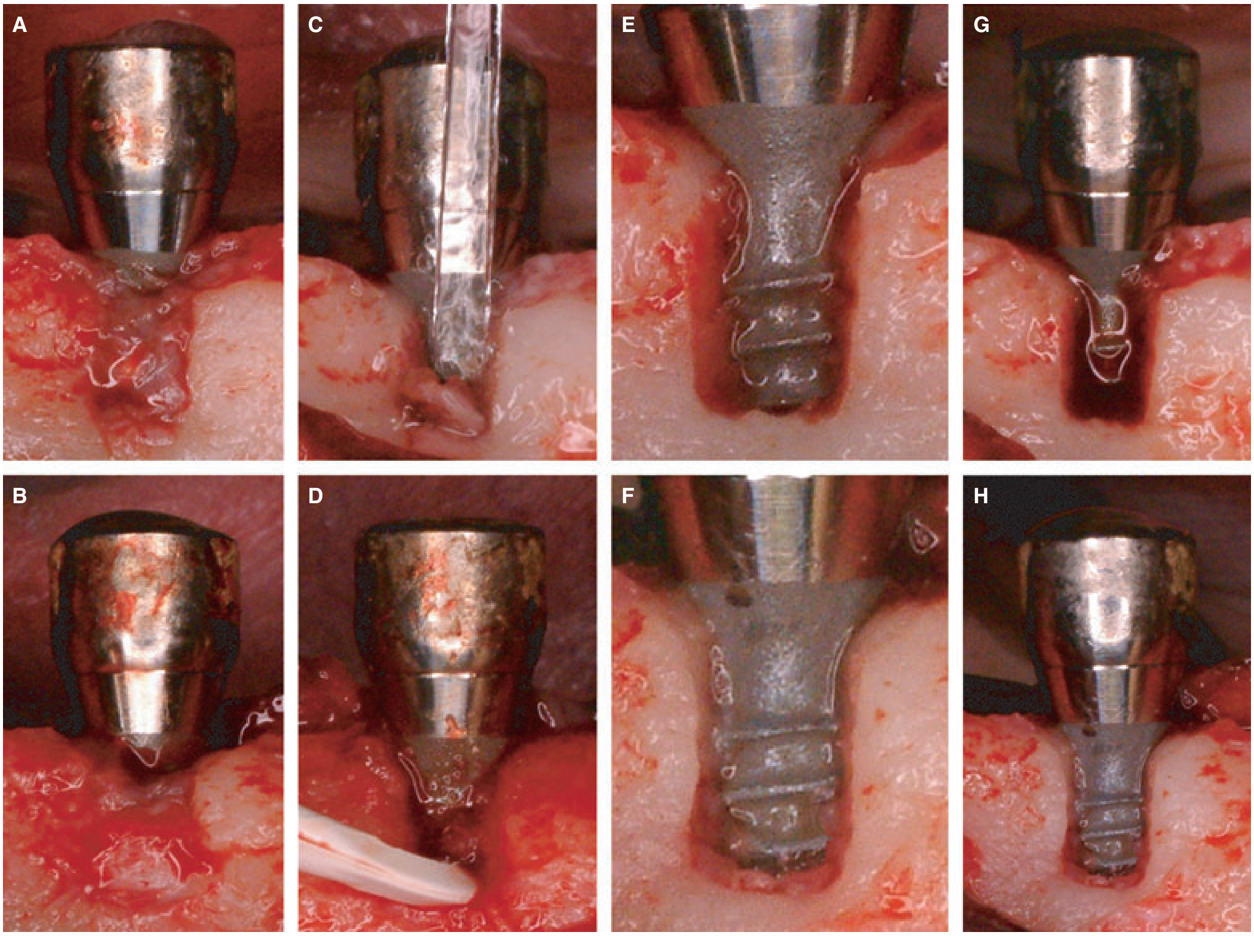

Fig. 10. Operative view of the surgical therapy procedures of experimentally induced peri-implant infection in dog. After elevation of the mucoperiosteal flap, the bone tissue adjacent to the defect had been resorbed to some extent and the defects were filled with diseased connective tissue (A, B). In the laser sites, degranulation and implant surface debridement were performed with Er:YAG laser irradiation under sterile water spray in contact mode at 62 mJ ⁄ pulse (panel setting 95–105 mJ ⁄ pulse, ED 10.0 J ⁄ cm^2 ⁄ pulse) and 20 Hz using a chisel tip (C). In the control sites, granulation tissue removal and implant surface debridement was performed using a plastic curet and then the titanium surface was meticulously cleaned by copious irrigation with physiological saline solution (D). Buccal view of the defects immediately after degranulation and implant surface debridement using an Er:YAG laser (E) or a plastic curet (F). Effective and safe granulation tissue removal and implant surface debridement with no macroscopically visible thermal damage were observed following Er:YAG laser irradiation of the implant surface and bone (the bleeding originating from the defect was removed to take the photograph). After debridement, a moderate amount of bleeding was generally observed from the bone defect in the laser-treated sites (G); this was different from the curet-treated sites, where generally no or substantially less bleeding was observed (H). [Photographs from Takasaki AA et al. Er:YAG laser therapy for peri-implant infection: a histological study. *Lasers Med Sci* 22: 143–157, 2007; with permission. *Lasers in Medical Science* © copyright (2007) Springer-Verlag London Limited].

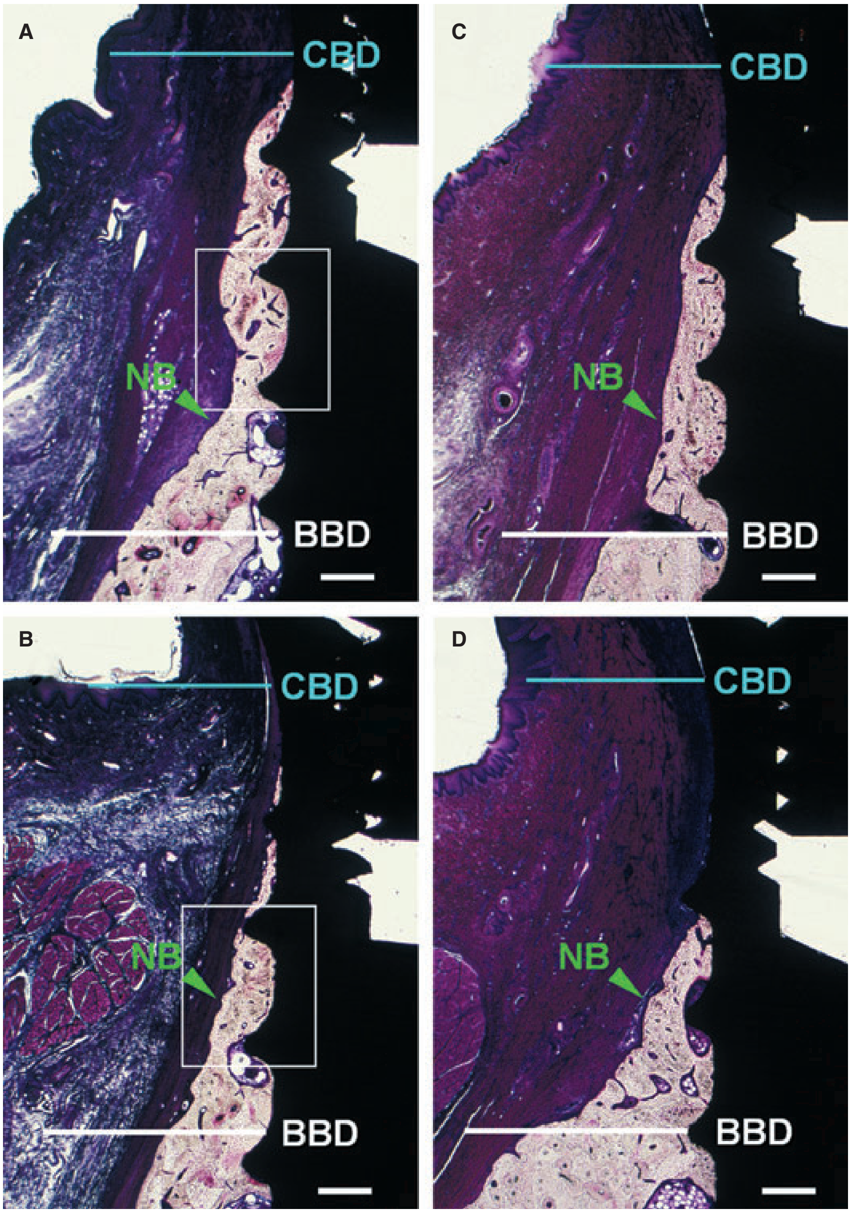

Fig. 11. Histological photomicrographs of the buccolingual nondecalcified sections parallel to the long axis of the implant in the center of the dehiscence defect 24 weeks following degranulation and debridement of the implant surface during surgical therapy of peri-implant infection using an Er:YAG laser or a plastic curet, as described in Fig. 10. (A, B) Histological sections showing the highest level of new bone formation in the laser and control groups, respectively. (C, D) Representative typical paired sections of laser and control sites. In both the laser-treated and plastic curet-treated sites, some degree of new bone formation with no structural differences was noted in the defect area. In the laser group, the newly-formed bone (NB) was more coronally extended along and in direct contact with the implant surface from the bottom of the bone defect (BBD) than the control. In the control group, only a small amount of new bone formation was in direct contact with the treated implant surface (Villanueva bone stain; bar, 500 μm; original magnification ×30.) CBD, coronal level of bone defect. [Photographs from Takasaki AA et al. Er:YAG laser therapy for peri-implant infection: a histological study. *Lasers Med Sci* 22: 143–157, 2007; with permission. *Lasers in Medical Science* © copyright (2007) Springer-Verlag London Limited].

Histologically, after 24 weeks of healing, the newly-formed bone was more coronally-positioned on the laser-treated implant surface in comparison to mechanical treatment. The Er:YAG laser-treated implant surface did not inhibit the formation of new bone, suggesting that the laser achieved decontamination of the implant surface with increased biocompatibility (Fig. 11).

Summary

Although most previous clinical studies have not shown significant differences between laser and conventional therapies, laser treatment generally showed tendencies for better results in animal studies. Further clinical and animal-comparative studies between different treatment approaches with laser treatment are necessary to prove the superiority of the application of lasers in the treatment of peri-implantitis. Nevertheless, based on previous reports, it can be concluded that application of lasers holds great promise as an alternative or adjunctive tool in the treatment of peri-implant diseases.

Other novel applications

Subgingival calculus detection

As a novel application in the dental clinical practice, lasers have been recently used to detect subgingival calculus. Correct diagnosis of the presence and extent of subgingival calculus is important in periodontal treatment planning and re-assessment following periodontal therapy. Also, complete removal and / or selective removal of subgingival calculus is important in order to achieve favourable wound healing. However, this objective is difficult to accomplish because the clinician has to rely on tactile feeling to judge the morphology and roughness of the root surface using conventional, manual methods such as a periodontal probe. Therefore, a more effective and accurate method of detecting subgingival calculus, especially when the calculus is located in the deepest portion of the pocket or on the root surface with complex anatomical contours, is necessary.

A new technology, primarily developed for caries diagnosis, also seems to be useful in this field of periodontology. This method for detection of subgingival calculus is based on differences in the fluorescence-emission properties of calculus and dental hard tissue. Several studies demonstrated that irradiation with a 655-nm diode laser induces significantly more fluorescent light emission in subgingival calculus than in the cementum. Fluorescence detectors of wavelengths between 633–635 and 700 nm have been employed for the clinical detection of subgingival periodontopathic conditions (68, 80). Increased values of laser fluorescence seem to be strongly related to the presence of calculus and those values seem to decrease after scaling. Based on those studies, it can be suggested that the application of laser fluorescence might be a useful tool for easy and precise detection of subgingival calculus.

An effective system for subgingival root debridement that combines an Er:YAG laser with diode laser fluorescence spectroscopy is also already being marketed mainly in the European countries (Key Laser III™; KaVo, Biberach, Germany). This Er:YAG laser-based substrate detection device incorporates a feedback-driven treatment mode and has been proven to be a viable alternative to previous subgingival scaling methods. This novel system holds great promise because the degree of root debridement can be assessed and subgingival root cleaning with the Er:YAG laser can be optimized with the aid of laser fluorescence spectroscopy (147). Although this system has been reported to perform selective removal of subgingival calculus (139), this system does not seem to achieve additional improvements in the clinical outcome of nonsurgical periodontal treatment using an Er:YAG laser alone (147).

However, it can be assumed that laser fluorescence, following technological improvements and further research, may be a potentially valuable tool for the clinical detection of subgingival calculus in the near future. Therefore, further clinical studies are necessary to validate the reliability of the detection of subgingival calculus using laser-induced fluorescence, and to demonstrate whether there is any superiority of using laser-fluorescence in nonsurgical therapy.

Low-level laser therapy

Lasers have been extensively applied in the treatment of periodontal disease. However, the various biological effects that lasers can produce on oral tissues are still not fully understood. Among the many physiological effects, it is important to recognize that the biostimulatory effects which laser irradiation produces on cells of the tissue during laser therapy might be beneficial by allowing faster wound healing in the process of periodontal tissue repair, which may not occur during conventional mechanical therapy. It has been suggested that low-level laser energy is responsible for these biomodulatory effects. Low-level laser therapy has been proposed as a new treatment approach for several diseases in the field of medicine. Low-level laser therapy has also been widely applied as part of the treatment of oral diseases in dentistry. Low-level laser therapy uses a light source that generates extremely pure light with a single wavelength. The effects that it can produce on the cell are related to photochemical reactions within cells, rather than thermal effects, although the mechanisms behind this are still unclear. Nevertheless, biostimulatory effects of laser irradiation, such as higher cell proliferation and wound healing, may have interesting applications in current therapy approaches.

Use of the biostimulatory effect of low-level laser therapy in postoperative therapy has recently been proposed owing to several possible benefits, such as the reduction of discomfort or pain (74), promotion of wound healing (115) and bone regeneration (91), and the suppression of inflammatory processes (115). Previous *in vitro* studies showed that low-level laser irradiation enhances the activation of human gingival fibroblasts and periodontal ligament cells to proliferate and release growth factors *in vitro* (73, 114, 128). Low-level laser therapy also decreases the amount of inflammation and accelerates wound healing by changing the expression of genes responsible for the production of inflammatory cytokines *in vivo* (123).

In a recent clinical study it was reported that following gingivectomy, the treatment of gingival tissue by low-level laser therapy led to accelerated wound healing compared to sites not treated with low-level laser therapy (109). Also, in another study, treatment with adjunctive low-level laser irradiation of periodontal pockets following scaling and root planing showed reduced gingival inflammation in comparison to scaling and root planing alone (115). Another study demonstrated that the additional application of low-level laser therapy during and after periodontal surgical-regenerative therapy using enamel matrix protein derivate in comparison to therapy with enamel matrix protein derivate alone resulted in greater improvement of clinical parameters and reduced postoperative pain (108).

Regarding osteogenesis, several *in vitro* studies have suggested that low-level laser therapy could promote new bone formation by inducing the proliferation and differentiation of osteoblasts (107, 158). It has been reported *in vitro* that low-level laser therapy increased the alkaline phosphatase activity (107) and mRNA expression of osteoblastic differentiation markers such as osteopontin (158), osteocalcin (107) and bone sialoprotein (158) in osteoblasts, and promoted bone nodule formation (107). Therefore, low-level laser therapy has been recently applied in the field of implant dentistry. Several animal studies investigated the additional effects of low-level laser therapy when applied additionally in sites treated by conventional methods, expecting increased and faster osseointegration of implants following irradiation. In fact, increased bone-to-implant contact and weight percentages of calcium and phosphorus were observed at the sites treated by additional low-level laser therapy compared with nonirradiated sites (65). In another study, osteocyte viability was significantly higher at early stages of healing in the bone sites irradiated by laser prior to implant placement than in nonirradiated implant sites (37). Also, low-level laser therapy appears to stimulate the proliferation and attachment of fibroblasts and osteoblasts cultured on titanium disks (64, 66).

Basic studies evaluating the effects of low-level laser therapy on periodontal tissues are still lacking and to date there are only a few published clinical studies regarding the effects of adjunctive low-level laser therapy in periodontal therapy. Thus, at present, the superiority of this novel treatment approach compared with conventional treatment has not been clearly demonstrated. Therefore, further clinical studies are needed to demonstrate the real beneficial effects of low-level laser therapy in periodontal and implant therapy.

Photodynamic therapy

Photodynamic therapy has been widely applied for the treatment of carcinomas in the field of medicine. Photodynamic therapy is based on the principle that a photoactivatable substance, the photosensitizer, binds to the target cell and can be activated by light of a suitable wavelength. During this process, free radicals are formed, thereby initiating tumor necrosis.

The application of systemic antibiotics in conjunction with mechanical therapy has been widely performed in periodontal therapy and is considered a valuable tool in the treatment of some forms of periodontal disease. However, it is now established that bacteria growing in biofilms are less susceptible to antibiotics as a result of protection within the plaque matrix (155). Also, frequent application of antibiotics may potentially increase the risk of bacterial resistance (172). Therefore, there is significant interest in the development of alternative antimicrobial concepts.

Recently, photodynamic therapy has been used to treat localized microbial infections because the free radicals that are formed during photodynamic therapy might be toxic effect to the bacteria. Researchers have proposed that this new therapeutic modality could be applied in periodontal therapy and it might have promise as a novel method of eliminating bacterial infection from periodontal pockets in the nonsurgical treatment of periodontitis.

Several studies have demonstrated the high bactericidal effect of photodynamic therapy and that it may be a valuable alternative to conventional mechanical approaches (33, 89, 111). Microbiological reduction was observed *in vivo* following photodynamic therapy in the treatment of peri-implantitis in dogs (52, 151). Also, it was reported in an animal model that photodynamic therapy can reduce periodontal disease progression and periodontal tissue destruction in experimentally induced periodontal disease (32). Recently, Sigusch et al. (152) demonstrated a reduction in the signs of periodontal inflammation in beagle dogs following treatment with photodynamic therapy.

In a recent split-mouth clinical study, it was demonstrated that nonsurgical periodontal treatment performed on patients with aggressive periodontitis, by applying photodynamic therapy alone, showed similar clinical improvements in comparison to scaling and root planing (33). Also, it has been demonstrated that scaling and root planing combined with photodisinfection, or the application of photodynamic therapy alone, leads to reduction of pocket depths and in clinical attachment gain in the nonsurgical treatment of periodontitis (5).

Although the application of photodynamic therapy in the treatment of periodontitis and peri-implantitis is an interesting therapeutic approach, current reports have not shown significant superior effects of photodynamic therapy compared with conventional mechanical therapy. Therefore, the potential effects of photodynamic therapy should be studied more extensively to establish the optimal conditions during clinical application. However, photodynamic therapy holds promise as a novel noninvasive treatment method that might be beneficial when applied alone or in conjunction with conventional mechanical periodontal and peri-implant therapy.

Summary and conclusions

In summary, the application of lasers has been recognized as an adjunctive or alternative approach in periodontal and peri-implant therapy. Soft tissue surgery is one of the major indications of lasers. CO_2, Nd:YAG, diode, Er:YAG and Er,Cr:YAG lasers are generally accepted as useful tools for these procedures. Laser treatments have been shown to be superior to conventional mechanical approaches with regards to easy ablation, decontamination and hemostasis, as well as less surgical and postoperative pain in soft tissue management. Laser or laser-assisted pocket therapy is expected to become a new technical modality in periodontics. The Er:YAG laser shows the most promise for root surface debridement, such as calculus removal and decontamination. Concerning the use of lasers for bone surgery, CO_2 and Nd:YAG lasers are considered unsuitable because of carbonization and degeneration of hard tissue. Currently, the Er:YAG laser is safe and efficient for periodontal bone surgery when used concomitantly with water irrigation. Application of lasers has also been considered in implant therapy. Based on previous reports, lasers, especially the Er:YAG laser, hold promise as an alternative treatment in the treatment of peri-implantitis. Application of photodynamic therapy in the treatment of periodontitis and peri-implantitis is a novel approach. However, to date the real superiority of photodynamic therapy for clinical improvements has not been demonstrated. Further studies are encouraged to understand in more detail the effects of lasers on biological tissues, including the periodontium, in order to ensure their safe and effective application during periodontal treatment. Among lasers currently available, the Er:YAG laser seems to provide the most suitable characteristics for various types of periodontal treatment.

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