Lasers in nonsurgical periodontal therapy

Akira Aoki, Katia Miyuki Sasaki, Hisashi Watanabe & Isao Ishikawa

This article reviews the current and potential applications of laser technology in nonsurgical therapy for the treatment of periodontal diseases. Based on its various characteristics, such as ablation or vaporization, hemostasis, and sterilization effect, laser treatment may serve as an adjunct or alternative to conventional, mechanical periodontal therapy. The Carbon dioxide (CO₂) and the Neodymium-doped:Yttrium-Aluminum-Garnet (Nd:YAG) lasers were previously approved for soft tissue treatment in periodontics (1, 2, 4), because of their superior ability of soft tissue ablation, accompanied by strong hemostatic and bactericidal effects (6, 37, 143, 170, 218). However, when these lasers are applied to dental hard tissues the result is major thermal damage, especially at a high-energy output, rendering them unsuitable for hard tissue treatment (56, 214). Recently, the Erbium-doped:Yttrium-Aluminum-Garnet (Er:YAG) laser was developed in dentistry (71, 85, 87). As it is capable of ablation in both soft and hard tissues, the Er:YAG laser can be used for periodontal hard tissue treatment such as root surface debridement, as well as soft tissue management (78). The use of lasers within the periodontal pocket has become a topic of much interest and is a promising field in periodontal therapy. This article deals with recent advances in nonsurgical laser therapy for periodontal disease, and will briefly describe the advantages and disadvantages of various laser types.

Nonsurgical periodontal therapy and lasers

In periodontal pockets, the root surfaces are contaminated with an accumulation of plaque and calculus, as well as infiltration of bacteria and bacterial endotoxins into cementum (5). Complete removal of these harmful substances is essential for the healing of periodontal tissue. Formation of biofilms on the exposed root surface within periodontal pockets impedes the infiltration of antibiotics, and therefore mechanical disruption of the biofilm is necessary during periodontal treatment (36).

Basically, the aim of periodontal treatment is to restore the biological compatibility of periodontally diseased root surfaces for subsequent attachment of periodontal tissues to the treated root surface. During the initial periodontal treatment, debridement of the diseased root surface is usually performed by mechanical scaling and root planing using manual or power-driven instruments. Power-driven instruments (power scalers) such as ultrasonic or air scalers are frequently used for root surface treatment as they render the procedure easy and less stressful for the operator, while improving the efficiency of treatment.

However, conventional mechanical debridement using curettes is still technically demanding and time consuming, and power scalers cause uncomfortable stress to the patients from noise and vibration. Complete removal of bacterial deposits and their toxins from the root surface and within the periodontal pockets is not necessarily achieved with conventional, mechanical therapy (5). In addition, access to areas such as furcations, concavities, grooves, and distal sites of molars is limited. Although systemic and local antibiotics are occasionally administered into periodontal pockets for the purpose of disinfection, with frequent use of antibiotics there is a potential risk of producing resistant microorganisms. Therefore, development of novel systems for scaling and root planing, as well as further improvement of currently used mechanical instruments, is required. As lasers can achieve excellent tissue ablation with strong bactericidal and detoxification effects, they are one of the most promising new technical modalities for nonsurgical periodontal treatment. Another advantage of lasers is that they can reach sites that conventional mechanical instrumentation cannot. The adjunctive or alternative use of lasers with...
conventional tools may facilitate treatment, and has the potential to improve healing.

Conventional mechanical treatment usually produces a smear layer and, sometimes, deep grooves on the root surface. A smear layer may adversely affect the healing of periodontal tissues as it contains bacteria and inflammatory substances such as debris of infected cementum and calculus (140). Therefore, ways to eliminate the smear layer have been investigated in recent years. Many researchers have examined the effects of root conditioning after mechanical debridement, using chemical agents such as tetracycline, citric acid, and ethylenediaminetetraacetic acid (EDTA). Root conditioning has been shown to remove the smear layer, and to expose collagen fibers and dentinal tubules, enhancing the histocompatibility and new connective tissue attachment with cementogenesis (25, 120, 154). Laser irradiation has been reported to exhibit bactericidal and detoxification effects without producing a smear layer, and the laser-treated root surface may therefore provide favorable conditions for the attachment of periodontal tissue.

Gingival curettage after scaling and root planing using mechanical instruments has been shown to have no added benefit over routine scaling and root planing (3, 41, 108, 146). Therefore, the root surface has been the focus of mechanical debridement, and root surface debridement alone is the main step of nonsurgical periodontal therapy at present. However, the poor clinical outcome of gingival curettage may have been due to the lack of an effective tool for soft tissue debridement. Contrary to mechanical treatment with conventional instruments, the excellent ablation of tissue with laser treatment is expected to promote healing of periodontal tissues, ablating the inflamed lesions and epithelial lining of the soft tissue wall within periodontal pockets. This procedure might be more effective for the treatment of residual pockets after initial therapy and during maintenance. Part of the laser energy scatters and penetrates during irradiation into periodontal pockets. The attenuated laser at a low energy level might then stimulate the cells of surrounding tissue, resulting in reduction of the inflammatory conditions (131, 162, 183), in cell proliferation (8, 103, 135), and in increased flow of lymph (184), improving the periodontal tissue attachment and possibly reducing postoperative pain. Although there is no clear evidence to date that laser applications improve clinical outcome due to the action of curettage (3), laser treatment has a potential advantage of accomplishing soft tissue wall treatment effectively along with root surface debridement, and should be further investigated.

**Characteristics of laser**

‘LASER’ is an acronym for Light Amplification by Stimulated Emission of Radiation. The physical principle of laser was developed from Einstein’s theories in the early 1900s, and the first device was introduced in 1960 by Maiman (114). Since then, lasers have been used in many different areas in medicine and surgery. Laser light is a man-made single photon wavelength. The process of lasing occurs when an excited atom is stimulated to emit a photon before the process occurs spontaneously. Spontaneous emission of a photon by one atom stimulates the release of a subsequent photon and so on. This stimulated emission generates a very coherent (synchronous waves), monochromatic (a single wavelength), and collimated form (parallel rays) of light that is found nowhere else in nature (28). Lasers can concentrate light energy and exert a strong effect, targeting tissue at an energy level that is much lower than that of natural light. The photon emitted has a specific wavelength that depends on the state of the electron’s energy when the photon is released. Two identical atoms with electrons in identical states will release photons with identical wavelengths. The characteristics of a laser depend on its wavelength (Table 1, Fig. 1).

The term ‘waveform’ describes the manner in which laser power is delivered over time, either as a continuous or as a pulsed beam emission. A continuous wave laser beam emits an uninterrupted beam at the output power set for as long as the switch is turned on. The pulsed beam may be delivered in two different modes: free-running pulse, in which pulsation occurs within the laser tube, and gated (chopped) pulse, in which the continuous wave beam is interrupted by a shutter at various rates. The gated pulse has the same maximum power as that set on the control panel of the laser, whereas the free-running pulse is the result of power storage for given time periods. Release of stored power within a very short time creates an emission that exhibits a peak power greater than the power selected on the control panel (28, 159).

When laser light reaches a tissue, it can reflect, scatter, be absorbed or be transmitted to the surrounding tissues (Fig. 2). In biological tissue, absorption is mainly due to the presence of free water molecules, proteins, pigments, and other macromolecules. The absorption coefficient strongly depends on the wavelength of the incoming laser irradiation. In thermal interactions, absorption by water molecules plays a significant role (129) (Fig. 3).
The absorption coefficient ($a$ : cm$^{-1}$) for water is 0.00029 for argon laser (514 nm), 0.020 for diode laser (800 nm), 0.61 for Nd:YAG laser (1,064 nm), 12,000 for Er:YAG laser (2,940 nm) and 860 for CO2 laser (carbon dioxide laser) (10,600 nm) (68, 129) (Fig. 3).

### Table 1. Type and wavelength of lasers

<table>
<thead>
<tr>
<th>Laser type</th>
<th>Wavelength</th>
<th>Color</th>
</tr>
</thead>
<tbody>
<tr>
<td>Excimer lasers</td>
<td>193 nm</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>Argon Fluoride (ArF)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Xenon Chloride (XeCl)</td>
<td>308 nm</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>Gas lasers</td>
<td>488 nm</td>
<td>Blue</td>
</tr>
<tr>
<td>Argon</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Helium Neon (HeNe)</td>
<td>637 nm</td>
<td>Red</td>
</tr>
<tr>
<td>Carbon Dioxide (CO$_2$)</td>
<td>10,600 nm</td>
<td>Infrared</td>
</tr>
<tr>
<td>Diode lasers</td>
<td>514 nm</td>
<td>Blue-green</td>
</tr>
<tr>
<td>Gallium Arsenide Phosphorus (InGaAsP)</td>
<td>655 nm</td>
<td>Red</td>
</tr>
<tr>
<td>Gallium Aluminum Arsenide (GaAlAs)</td>
<td>670–830 nm</td>
<td>Red-infrared</td>
</tr>
<tr>
<td>Gallium Arsenide (GaAs)</td>
<td>840 nm</td>
<td>Infrared</td>
</tr>
<tr>
<td>Indium Gallium Arsenide (InGaAs)</td>
<td>980 nm</td>
<td>Infrared</td>
</tr>
<tr>
<td>Solid state lasers</td>
<td>532 nm</td>
<td>Green</td>
</tr>
<tr>
<td>Frequency-doubled Alexandrite</td>
<td>337 nm</td>
<td>Ultraviolet</td>
</tr>
<tr>
<td>Potassium Titanyl Phosphate (KTP)</td>
<td>1,064 nm</td>
<td>Infrared</td>
</tr>
<tr>
<td>Neodymium:YAG (Nd:YAG)</td>
<td>2,780 nm</td>
<td>Infrared</td>
</tr>
<tr>
<td>Holmium:YAG (Ho:YAG)</td>
<td>2,790 nm</td>
<td>Infrared</td>
</tr>
<tr>
<td>Erbium, chromium:YSGG (Er,Cr:YSGG)</td>
<td>2,940 nm</td>
<td>Infrared</td>
</tr>
<tr>
<td>Erbium:YSGG (Er:YSGG)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Erbium:YAG (Er:YAG)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fig. 1. Electromagnetic spectrum and wavelengths of lasers.

Fig. 2. Effects of laser irradiation on tissue. When laser light impinges on tissue, it can reflect, scatter, be absorbed or transmitted to the surrounding tissue.

### Application of lasers in periodontal therapy

Lasers were first employed in dentistry in hard tissue treatments, such as caries removal and cavity preparation, as a substitute for mechanical cutting and drilling. After the discovery of the ruby laser in 1960, Goldman and coworkers (65) attempted caries removal in vitro using the ruby laser in 1964. Since then, many researchers have investigated the effects of various lasers such as the argon, CO$_2$, and Nd:YAG lasers on dental hard tissues and caries (95, 190). However, previous laser systems were basically not indicated for hard tissue procedures due to major thermal damage (55, 214). Thus, these laser systems showed only limited potential for caries prevention.
and for the polymerization of light-cured restorative materials (142) in the field of preventive and operative dentistry.

The initial and most important stage of periodontal therapy is the nonsurgical mechanical debridement of periodontally diseased root surfaces. In 1965, Kinersly et al. (95) had already reported the possibility of removing dental calculus by ruby laser. However, they warned that limiting the vaporization selectively to calculus without damaging the underlying tooth might present clinical problems.

Since the periodontium is composed of gingiva, periodontal ligament, cementum, and alveolar bone, both soft and hard tissues are always targeted when using lasers for the treatment of periodontal lesions. The commonly used high power lasers CO₂ and Nd:YAG are capable of excellent soft tissue ablation, and have an adequate hemostatic effect. As such, these lasers have been generally approved for soft tissue management in periodontics and oral surgery (1, 2, 4, 137, 159). However, these lasers are not useful for treatment of the root surface or alveolar bone, due to carbonization of these tissues and major thermal side-effects on the target and surrounding tissues (159). Until the beginning of the 1990s, the use of laser systems in periodontal therapy was limited to soft tissue procedures, such as gingivectomy and frenectomy (1, 2, 137, 160), as application to periodontal hard tissues had previously proved to be clinically unpromising.

In the early and mid 1990s, scientific research was begun on root surface debridement and pocket curettage using an Nd:YAG laser. The clinical application of the Nd:YAG laser had already been tried by general practitioners because its convenient, flexible fiber optic delivery system made it appropriate for use in periodontal pockets (124).

Meanwhile, in 1988, Hibst et al. (72) and, in 1989, Keller & Hibst (71, 87) and Kayano et al. (85) reported the possibility of dental hard tissue ablation by Er: YAG laser irradiation, which is highly absorbed by water. Since then, numerous studies on hard tissue treatment using the Er:YAG laser have indicated the ability of this laser to ablate dental hard tissues and caries lesions without producing major thermal side-effects. Promising results in basic and clinical application have been demonstrated in the field of caries therapy (11, 34, 76, 86, 89, 92, 115). Later, in the mid 1990s, Aoki et al. (10) and Keller et al. (90) began to investigate the application of the Er:YAG laser for periodontal hard tissue procedures, such as dental calculus removal and decontamination of the diseased root surface. A number of basic studies on Er:YAG laser application to root surface treatment followed and, recently, promising results have been reported in clinical studies on nonsurgical pocket therapy. Application of the Er:YAG laser for bone surgery has been also studied in vitro and in vivo (15, 94, 141, 165, 204). Development of this laser brought the prospect of hard tissue treatment in periodontics (78) and endodontics (42, 185), as well as in operative dentistry including pediatric dentistry (38, 83).

The diode lasers as well as Nd:YAG lasers are currently used for pocket curettage by clinicians because of their flexible fiber delivery system, which is suitable for pocket insertion. However, to date, there is a shortage of basic and clinical research providing scientific support for these procedures.

In the field of dentistry, Nd:YAG, CO₂, diodes, Er: YAG, Er,Cr:YSGG, Argon, excimer and alexandrite lasers are being studied in vitro or are in clinical use (Table 2). Their use in the treatment of periodontal pockets and/or debridement of the periodontally diseased root surface is presently under investigation. Advances in research on clinical application of each laser system for nonsurgical periodontal therapy are discussed in the next section of this chapter.

**Characteristics and current research on different laser systems**

**CO₂ laser**

**Characteristics**

The CO₂ laser has a wavelength of 10,600 nm and is used as both a pulsed and a continuous wave laser.
This laser is readily absorbed by water and therefore is very effective for the surgery of soft tissues, which have a high water content. The primary advantage of CO₂ laser surgery over the scalpel is the strong hemostatic and bactericidal effect. Very little wound contraction and minimal scarring are other advantages of laser surgery, especially for the CO₂ laser (113). The CO₂ laser has been used for soft tissue surgery since the early 1970s (27, 54, 112, 134, 206). In 1976, it was approved by the US Food and Drug Administration (FDA) for soft tissue surgery, including the surgery of the oral tissues.

Since the CO₂ laser (10,600 nm) produces severe thermal damage, such as cracking, melting, and carbonization when applied to hard tissues (111, 168), its use has been limited to soft tissue procedures. Even though the water absorption coefficient of the CO₂ laser is approximately one-tenth that of the Er:YAG laser, it still shows a relatively high level (Fig. 3). Considering only the water absorption coefficient, we may assume that the CO₂ laser (10,600 nm) to some extent demonstrates similar hard tissue ablation to the Er:YAG laser. However, the CO₂ laser is also highly absorbed by the main, mineral components of hard tissue, especially phosphate ions (~PO₄) in the carbonated hydroxyapatite (44, 45, 58, 59, 97). The energy applied is readily absorbed in the hard tissue but causes instantaneous heat accumulation in the irradiated inorganic components, resulting in carbonization of organic components and melting of the inorganic ones, instead of the water-mediated physical collapse of the hard tissue observed in Er:YAG laser irradiation (59, 180).

The CO₂ laser is absorbed at the tissue surface with very little scatter or penetration. Since ablation is mainly due to the action of heat generation, carbonization easily occurs on the irradiated surface but the heat produced does not scatter. Therefore, the CO₂ laser produces a relatively thin layer of thermally changed tissue (coagulation) around the ablated site. The width of the coagulation layer was reported to be 100–300 µm in an incision of pigskin with the continuous mode CO₂ laser at 6 W (16). Tissue penetration from this laser irradiation will be approximately

<table>
<thead>
<tr>
<th>Laser type</th>
<th>Current/Potential dental application</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Excimer lasers</strong></td>
<td>Argon Fluoride (ArF) Hard tissue ablation, Dental calculus removal</td>
</tr>
<tr>
<td></td>
<td>Xenon Chloride (XeCl)</td>
</tr>
<tr>
<td><strong>Gas lasers</strong></td>
<td>Argon (Ar) Curing of composite materials, Tooth whitening, Intraoral soft tissue surgery, Sulcular</td>
</tr>
<tr>
<td></td>
<td>debridement (subgingival curettage in periodontitis and peri-implantitis)</td>
</tr>
<tr>
<td></td>
<td>Helium Neon (HeNe) Analgesia, Treatment of dentin hypersensitivity, Aphthous ulcer treatment</td>
</tr>
<tr>
<td></td>
<td>Carbon Dioxide (CO₂) Intraoral and implant soft tissue surgery, Aphthous ulcer treatment, Removal</td>
</tr>
<tr>
<td></td>
<td>of gingival melanin pigmentation, Treatment of dentin hypersensitivity, Analgesia</td>
</tr>
<tr>
<td><strong>Diode lasers</strong></td>
<td>Indium Gallium Arsenide Phosphorus (InGaAsP) Intraoral general and implant soft tissue surgery</td>
</tr>
<tr>
<td></td>
<td>Gallium Aluminum Arsenide (GaAlAs) and Gallium Arsenide (GaAs) Curing of composite materials, Tooth</td>
</tr>
<tr>
<td></td>
<td>Whitening, Intraoral soft tissue surgery, Sulcular debridement (subgingival curettage in periodontitis</td>
</tr>
<tr>
<td></td>
<td>and peri-implantitis), Analgesia, Treatment of dentin hypersensitivity, Pulpotomy, Root canal</td>
</tr>
<tr>
<td></td>
<td>disinfection, Removal of enamel caries, Aphthous ulcer treatment, Removal of gingival melanin</td>
</tr>
<tr>
<td></td>
<td>pigmentation</td>
</tr>
<tr>
<td><strong>Solid state lasers</strong></td>
<td>Frequency-doubled Selective ablation of dental plaque and calculus</td>
</tr>
<tr>
<td></td>
<td>Alexandrite, Neodymium:YAG (Nd:YAG) Intraoral soft tissue surgery, Sulcular debridement (subgingival</td>
</tr>
<tr>
<td></td>
<td>curettage in periodontitis), Analgesia, Treatment of dentin hypersensitivity, Pulpotomy, Root canal</td>
</tr>
<tr>
<td></td>
<td>disinfection, Removal of enamel caries, Aphthous ulcer treatment, Removal of gingival melanin</td>
</tr>
<tr>
<td></td>
<td>pigmentation</td>
</tr>
<tr>
<td></td>
<td><strong>Erbium group</strong> Caries and calculus detection</td>
</tr>
<tr>
<td></td>
<td>Erbium:YAG (Er:YAG), Erbium:YSGG (Er:YSGG), Erbium,chromium:YNSSG (Er, Cr:YSGG) Selective ablation</td>
</tr>
<tr>
<td></td>
<td>of dental plaque and calculus</td>
</tr>
<tr>
<td></td>
<td>Introra oral soft tissue surgery, Sulcular debridement (subgingival curettage in periodontitis and</td>
</tr>
<tr>
<td></td>
<td>peri-implantitis), Analgesia, Treatment of dentin hypersensitivity, Pulpotomy, Root canal disinfection</td>
</tr>
<tr>
<td></td>
<td>Screening of root surfaces, Osseous surgery, Treatment of dentin hypersensitivity, Analgesia, Pulpotomy</td>
</tr>
<tr>
<td></td>
<td>Root canal treatment and disinfection, Aphthous ulcer treatment, Removal of gingival melanin/metal-</td>
</tr>
<tr>
<td></td>
<td>tattoo pigmentation</td>
</tr>
</tbody>
</table>

| Table 2. Current and potential applications of lasers in dentistry |
0.5 mm deep, depending on power density (160). In the field of periodontics, there have been several reports on laser application for gingivectomy and gingivoplasty in the late 1980s (19, 138, 139, 160).

Transmission of the CO₂ laser through optical fibers was very difficult and therefore the CO₂ laser system previously employed mirror systems using articulated arms for laser beam delivery. Recently, new flexible fiber optic delivery and hollow tube wave-guiding systems have been developed, along with the development of contact tips. These advances may render the use of the CO₂ laser for periodontal pockets possible in the near future.

**Basic and clinical studies on root surface preparation and calculus removal**

Several basic studies have shown the effects of continuous wave CO₂ laser irradiation on root surfaces. The continuous wave CO₂ laser readily produces carbonization, melting, and cracking of root cementum and dentin (80, 164, 167, 182, 187) (Fig. 4, Table 3).

Spencer et al. (187) found cyan-derived toxic products, such as cyanamide and cyanate ions, on the carbonized layer of the CO₂ lased (continuous wave, 8 W) root surface by chemical analysis using Fourier transformed infrared (FTIR) spectroscopy. Tucker et al. (200) evaluated the effects of the CO₂ laser on calculus *in vitro* and reported that the pulsed CO₂ laser at 6 W and 20 Hz (pulse duration: 0.01 s) was able to remove dental plaque on the root surface, whereas only melting and carbonization occurred on the dental calculus of extracted teeth. In an animal study, Gopin et al. (66) demonstrated that the root surface treated by pulsed CO₂ laser (pulse duration: 0.01 s) at 6 W and 20 Hz, featuring a residual char layer, inhibited periodontal soft tissue attachment.

Misra et al. (118) examined the root conditioning effects of the defocus mode CO₂ laser after scaling and root planing *in vitro*. Laser irradiation at 3 W for 1 s completely removed the smear layer with minimal change in the diameter of the dentinal tubules; however, irradiation times of 1.2 and 1.4 s produced surface charring and carbonization, and were totally ineffective in exposing the dentinal tubules. Barone et al. (20) investigated the effects of the pulsed defocus mode CO₂ laser. The CO₂ laser at 2.0 W and 4 Hz with 4.0 mm spot size did not result in any extensive damages to the root surface, which was flat and smooth with apparent fusion of the smear layer. They concluded that the pulsed defocus mode may present the advantage of decontaminating the root surface. Crepsi et al. (35) reported that after the pulsed defocus mode CO₂ laser treatment at 2 W and 1 Hz, the periodontally diseased root surface showed the highest number of tightly attached fibroblasts compared with the nontreated control and scaling and root planing (SRP) alone. They concluded that pulsed defocus mode CO₂ laser treatment combined with mechanical instrumentation constitutes a useful tool for root conditioning. Coffelt et al. (31) found that, when used at an energy density between 11 and 41 mJ/cm² in the defocused mode, the CO₂ laser destroyed microbial colonies without inflicting undue damage to the root surfaces.

Thus, the CO₂ laser, when used with high-energy output, especially in a continuous wave mode, is not appropriate for calculus removal and root surface debridement due to major thermal side-effects, such as carbonization. However, when used with relatively low energy output in a pulsed and/or defocused mode, this laser may have root conditioning, detoxification and bactericidal effects on the contaminated root surfaces.

Miyazaki et al. (119) applied CO₂ laser irradiation for pocket treatment on the external surface of the marginal gingiva. They used a continuous wave mode CO₂ laser (2.0 W, 120 s) and reported decreased inflammation and probing depth after treatment. However, so far there have been no reported clinical studies on application of the CO₂ laser in periodontal pockets.

**Nd:YAG laser**

**Characteristics**

The Nd:YAG laser is a free-running pulsed wave laser with a wavelength of 1,064 nm. Unlike the CO₂ and Er:YAG lasers, the Nd:YAG laser has low absorption in
water, and the energy scatters or penetrates into the biological tissues. In water, the Nd:YAG laser will theoretically penetrate to a depth of 60 mm before it is attenuated to 10% of its original strength (4).

The photothermal effect of the Nd:YAG laser is useful for soft tissue surgery. Due to the characteristics of penetration and thermogenesis, the Nd:YAG laser produces a relatively thick coagulation layer on the lased soft tissue surface, and thereby shows strong hemostasis. Hence, the Nd:YAG laser is basically effective for ablation of potentially hemorrhagic soft tissue. The width of the coagulation layer was 0.3–0.8 mm in an incision of bovine oral soft tissue in vitro at 3–10 W (136, 208, 212).

In dentistry, soft tissue surgery using the Nd:YAG laser has been widely accepted (117, 125, 137, 157, 207). In 1990, the FDA approved soft tissue removal by means of a pulsed Nd:YAG laser (193). White et al. (210) successfully used the Nd:YAG laser for intraoral soft tissue application without anesthesia, and with minimal bleeding compared to scalpel surgery. It is easy to deliver the Nd:YAG laser by a flexible optical fiber with a contact tip of 400 μm (core diameter: 320 μm) suitable for pocket insertion, and basic research and clinical trials have been performed on periodontal pocket curettage and root surface debridement. In 1997, the FDA approved sulcular debridement by means of a pulsed Nd:YAG laser (193).

The Nd:YAG laser is not suitable for ablation of intact hard tissues. However, caries removal using this laser is possible to some extent (21, 211). White et al. (211) reported a safe and effective procedure for selective removal of enamel caries with the Nd:YAG laser, and the FDA approved removal of enamel (first degree) caries using an Nd:YAG laser in 1999 (193). As the Nd:YAG laser is well absorbed by dark substances, Indian ink or other kinds of black pigment are often applied to increase the efficiency of ablation (82).

### Basic studies

**Calculus removal:** In an in vitro study, Tseng & Liew (198, 199) demonstrated that partial removal and detachment of the calculus from the root surface was achieved with the Nd:YAG laser at 2.0 or 2.75 W and 20 Hz. However, melting of calculus and thermal

<table>
<thead>
<tr>
<th>Author and Year</th>
<th>References</th>
<th>Laser parameters</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shariati et al. 1993</td>
<td>(182)</td>
<td>5 or 10 W, CW 5–11 W, 10 or 20 Hz</td>
<td>Carbonization, melting and cracking of root cementum and dentin</td>
</tr>
<tr>
<td>Israel et al. 1997</td>
<td>(80)</td>
<td>0.5 W, CW</td>
<td></td>
</tr>
<tr>
<td>Sasaki et al. 2002</td>
<td>(164, 167)</td>
<td>8 W, CW 0.5 W, CW</td>
<td>Presence of cyan-derived toxic products on the carbonized layer</td>
</tr>
<tr>
<td>Spencer et al. 1996</td>
<td>(187)</td>
<td>6 W, 20 Hz</td>
<td>Dental plaque removal and calculus carbonization</td>
</tr>
<tr>
<td>Sasaki et al. 2002</td>
<td>(167)</td>
<td>2–5 W, 10 or 20 Hz</td>
<td>Destruction of microbial colonies without inflicting undue damage to the root surfaces in defocused mode</td>
</tr>
<tr>
<td>Tucker et al. 1996</td>
<td>(200)</td>
<td>Inhibition of periodontal tissue attachment by residual char layer in vivo</td>
<td></td>
</tr>
<tr>
<td>Coffelt et al. 1997</td>
<td>(31)</td>
<td>3 W, CW defocus</td>
<td>Root conditioning effects in defocused irradiation</td>
</tr>
<tr>
<td>Gopin et al. 1997</td>
<td>(66)</td>
<td>2 W, 1 Hz defocus</td>
<td>Increased fibroblast attachment after root conditioning in pulsed defocus mode</td>
</tr>
<tr>
<td>MIS et al. 1999</td>
<td>(118)</td>
<td>Decreased inflammation and probing depth at 12 weeks after pocket treatment by irradiation on the external surface of the marginal gingiva (see Table 5)</td>
<td></td>
</tr>
<tr>
<td>Barone et al. 2002</td>
<td>(20)</td>
<td>Root decontamination effects on the root surface in pulsed defocus mode</td>
<td></td>
</tr>
<tr>
<td>Crespi et al. 2002</td>
<td>(35)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Miyazaki et al. 2003</td>
<td>(197)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

CW: continuous wave.
damage was noted in localized areas of the original cementum and even dentin after irradiation at high power (198). They also reported that, after laser irradiation, removal of remaining calculus by curettes was facilitated (198, 199). Arcoria & Vitasek-Arcoria (17) assessed the effects of the Nd:YAG laser on calculus removal from root surfaces in vitro. Nd:YAG laser irradiation was performed at the calculus–cementum interface in contact mode at 1.5 or 3.0 W (15 Hz) with the tip inclined 45° to the root surface. The integrity of the calculus–root surface attachment was not appreciably affected by 1.5 W irradiation, whereas 3.0 W irradiation detached the calculus without root surface damage, similarly to conventional hand instrumentation. In an in vitro study, Radvar et al. (144) reported that Nd:YAG laser irradiation, perpendicular to the root surface, at 0.5–2.0 W (50 or 100 mJ/pulse, 10 or 20 Hz) caused greater ablation of calculus than either cementum or dentin. However, the specimens with complete evaporation of calculus also showed some degree of damage to the underlying cementum (Table 4).

Judging by the above, limited studies, the ability of the Nd:YAG laser to remove calculus is insufficient, and removal of calculus at a level equivalent to mechanical treatment can not be expected clinically. As subgingival calculus is originally dark in color, the Nd:YAG laser has the advantage of being absorbed

<table>
<thead>
<tr>
<th>Table 4. Nd:YAG laser – Basic studies on calculus removal and root surface treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Author and Year</strong></td>
</tr>
<tr>
<td>Tseng &amp; Liew 1990, 1991</td>
</tr>
<tr>
<td>White et al. 1991</td>
</tr>
<tr>
<td>Arcoria &amp; Vitasek-Arcoria 1992</td>
</tr>
<tr>
<td>Morlock et al. 1992</td>
</tr>
<tr>
<td>Spencer et al. 1992</td>
</tr>
<tr>
<td>Trylovich et al. 1992</td>
</tr>
<tr>
<td>Ito et al. 1993</td>
</tr>
<tr>
<td>Fukuda et al. 1994</td>
</tr>
<tr>
<td>Thomas et al. 1994</td>
</tr>
<tr>
<td>White et al. 1994</td>
</tr>
<tr>
<td>Radvar et al. 1995</td>
</tr>
<tr>
<td>Wilder-Smith et al. 1995</td>
</tr>
<tr>
<td>Spencer et al. 1996</td>
</tr>
<tr>
<td>Liu et al. 2002</td>
</tr>
</tbody>
</table>

*Calculated from data presented in paper. CW: continuous wave.
well into subgingival calculus. Use of higher energy levels may ablate calculus more efficiently but may be inappropriate for clinical usage due to increased thermal side-effects.

**Root surface treatment:** Several basic studies have shown the effects of Nd:YAG laser irradiation on root surfaces. Nd:YAG laser produced thermal changes such as carbonization, melting, and resolidification of root cementum and dentin (80, 123, 187, 189, 197) (Fig. 5, Table 4).

Morlock et al. (123) showed that the Nd:YAG laser at 1.25–1.50 W (62.5–75 mJ/pulse, 20 Hz) produced surface pitting and crater formation with charring, carbonization, melting, and crater production, even when irradiation was performed parallel to the surface. Spencer et al. (189) reported a decrease in the protein/mineral ratio in cementum samples lased with the Nd:YAG laser at 0.8 W (80 mJ/pulse and 10 Hz) using FTIR analysis. They considered that the decreased protein/mineral ratio and the potential surface contamination with protein by-products might ultimately affect cell reattachment at the cementum surface. Later, they suggested that the protein by-products would be cyanamide and cyanate ions (39, 40, 187).

Trylovich et al. (197) showed that the root surface after Nd:YAG laser irradiation at 0.8 W (80 mJ/pulse, 10 Hz) was unfavorable for fibroblast attachment *in vitro*. Thomas et al. (195) also reported that the nondiseased root surfaces treated at 1.5 W (75 mJ/pulse, 20 Hz) with water coolant exhibited a significantly decreased fibroblast attachment, but the root planing or polishing with air-powder abrasive that followed, increased the cell attachment. They concluded that alterations in the laser-irradiated surface are reversible and additional root treatment following laser irradiation appears essential to render the root surface biocompatible. FTIR spectroscopy of the lased root surface revealed reduction of the Amide II band, suggesting denaturation of surface protein upon laser exposure.

Nd:YAG laser treatment has been reported to remove the smear layer on the root surface. In Ito et al.’s study (81) Nd:YAG laser was effective in removing the smear layer after conventional root planning. However, the extremely high energy level used (20 W, continuous wave [CW]) could not be used clinically. Wilder-Smith et al. (215) examined the effect of smear layer removal using the Nd:YAG laser at 5 W (pulse durations and intervals of 0.1 s; 5 Hz and calculated energy output 1,000 mJ/pulse) without coolant. Although the smear layer was removed without microstructural changes of the hard tissue, a significant rise in the intrapulpal and root surface temperature occurred. They concluded that the irradiation parameters used may not be appropriate for clinical use.

Interestingly, Fukuda et al. (62) performed Nd:YAG laser irradiation to the periodontally diseased root surface of extracted teeth, and reported that the Nd:YAG laser at 0.3–0.5 W (30–50 mJ/pulse, 10 Hz, 2–4 s) could inactivate the endotoxin in the superficial layer of the root surface. Liu et al. (110) explored the *in vitro* effectiveness of the Nd:YAG laser for the elimination of cementum-bound endotoxin by measuring interleukin (IL)-1β changes in stimulated monocytes. Nd:YAG laser varying between 50 mJ/pulse and 10 Hz and 150 mJ/pulse and 20 Hz for 2 min did not seem to be effective in destroying diseased cementum endotoxin. However, in their study, the thermal effect of Nd:YAG laser would have been weakened by noncontact irradiation with a long distance (1.5 cm) to the moistened cementum particles.

Regarding the bactericidal effect, in an *in vitro* study, White et al. (209) examined the decontamination effects of the Nd:YAG laser on root surface. They treated dentin sections contaminated with bacteria using the Nd:YAG laser, and reported that there was a 6-log reduction in *Bacillus subtilis* and *Escherichia coli* after 2 min of laser exposure greater than 0.5 W.

**Clinical studies**

Cobb et al. (29) performed Nd:YAG laser irradiation into periodontal pockets *in vivo* in 18 teeth from eight patients, and examined the effects of root debridement using a power of 1.75–3.0 W (87.5–150 mJ/...
pulse, 20 Hz), either alone or in combination with manual instrumentation. Application of the Nd:YAG laser resulted in ineffective and patchy removal of calculus from the root surface. The remaining calculus had a characteristic porous surface due to carbonization, melting, and resolidification but the surface was free of microbial plaque. They suggested that laser therapy should be followed by mechanical debridement. They reported the effect of Nd:YAG laser on both root surface and subgingival microflora in periodontal pockets, employing teeth that required extraction. DNA probe analysis showed a decreased number of bacteria in periodontal pockets after laser treatment. In addition, there were root surface alterations similar to those observed in the in vitro studies.

Horton & Lin (75) compared subgingival application of the Nd:YAG laser with conventional scaling and root planing. Each of three segments in 15 patients received Nd:YAG laser irradiation (2 W: 100 mJ/pulse and 20 Hz, 2 min), scaling and root planing by curette, or no treatment. The subgingival application with the Nd:YAG laser was equally or more effective than scaling and root planing in reducing or inhibiting recolonization of specific bacterial species and, though less effective in removing calculus, was at least equally effective on measures of probe depths and attachment loss.

Gold & Vilardi (64) performed Nd:YAG laser curettage in vivo, and studied microscopically 24 specimens of gingival tissue from six patients following the laser application at 1.25 and 1.75 W (62.5 and 87.5 mJ/pulse, 20 Hz). The pulsed Nd:YAG laser removed pocket-lining epithelium in moderately deep periodontal pockets without causing necrosis or carbonization of the underlying connective tissue. Radvar et al. (145) performed pocket treatment using Nd:YAG laser at a low power level of 0.5 or 0.8 W (50 or 80 mJ/pulse, 10 Hz), or scaling and root planing in 80 periodontally affected sites of teeth scheduled for extraction in 11 patients. Scanning electron microscope examination revealed that the low Nd:YAG laser energy levels did not cause any heat damage to the root surface, but failed to improve the clinical and microbiological parameters of periodontal disease as compared to scaling and root planing.

Ben Hatit et al. (22) compared the in vivo effects of conventional scaling plus Nd:YAG laser at 0.8–1.5 W (100 mJ/pulse, 8–15 Hz) treatment with those of scaling alone, on root cementum and levels of periodontopathic bacteria, in 150 sites from 14 patients. The post-treatment reduction of levels of periodontopathic bacteria in the conventional scaling followed by laser treatment group was significantly greater than the scaling alone control. However, scanning electron microscope examination of the specimens treated with the Nd:YAG laser exhibited different root surface alterations.

Neil & Mellonig (128) performed a double-blind, randomized, controlled clinical trial for sulcular debridement on 186 teeth from 10 patients using a split-mouth design to compare the adjunctive use of the pulsed Nd:YAG laser at 2 W (80 mJ/pulse, 25 Hz) to scaling and root planing alone in the nonsurgical treatment of moderate to advanced adult periodontitis. The reduction of probing depth for 6 months after treatment was similar between the scaling and root planing plus laser therapy and scaling and root planing alone, but the scaling and root planing plus laser therapy showed significantly greater improvements in gingival index and gingival bleeding index at specific time points. The mean attachment level of laser-treated pockets also showed a tendency to improve steadily for 6 months, whereas the scaling and root planing group showed a reduction in attachment level.

Liu et al. (109) performed a randomized, controlled clinical trial in a split-mouth design, comparing the effects of Nd:YAG laser treatment with scaling and root planing treatment on crevicular IL-1β levels, which is closely associated with periodontal destruction, in 52 sites from eight patients. Data showed that laser therapy alone (3 W: 150 mJ/pulse and 20 Hz) was less effective than traditional SRP for the reduction of crevicular IL-1β. Laser treatment followed by SRP after 6 weeks showed greater reduction of IL-1β and more clinical improvement than scaling and root planing followed by laser treatment after 6 weeks. No additional benefit was found when laser treatment was used secondary to traditional scaling and root planing therapy.

Miyazaki et al. (119) compared the effectiveness of the Nd:YAG and CO2 laser treatment to that of ultrasonic scaling in periodontal pockets of chronic periodontitis patients. The 41 sites of 18 patients were randomly assigned for treatment with the Nd:YAG laser alone (2.0 W: 100 mJ/pulse and 20 Hz, 120 s), the CO2 laser alone (2.0 W, 120 s), or ultrasonic scaling alone (maximum power, 120 s). Decreased inflammation and probing depth were observed in all three groups after treatment. There were significant decreases in both Porphyromonas gingivalis and the amount of gingival crevicular fluid in the Nd:YAG and scaling groups. The Nd:YAG group also tended to show a decrease in IL-1 level. Nd:YAG laser and ultrasonic scaling treatments showed significant improvements regarding the clinical
parameters and subgingival microflora compared to the baseline, but no significant difference was observed between the three groups.

Various combinations of irradiation parameters have been reported for the clinical use of the Nd:YAG laser for pocket treatment (208). White (208) recommended 1.5 W (100 mJ/pulse, 15 Hz) irradiation for removal of the sulcular diseased tissue and 2.0 W (100 mJ/pulse, 20 Hz) irradiation for coagulation of soft tissue wall after mechanical debridement. Coluzzii (33) recommended laser soft tissue curettage at 1.8 W (30 mJ/pulse, 60 Hz) after mechanical debridement, followed by irradiation at 2 W (100 mJ/pulse, 20 Hz) for hemostasis and bacterial reduction. Gutknecht et al. (67) suggested the use of the Nd:YAG laser at 2 W (100 mJ/pulse, 20 Hz) for curettage before mechanical debridement to reduce the risk of bacteremia after the scaling and root planing procedures, and to facilitate mechanical debridement.

**Summary of the Nd:YAG laser clinical application**

In 1997, the US FDA approved the application of the Nd:YAG laser for sulcular debridement or soft tissue curettage (193). It was the first approval of laser application in periodontal pockets by the FDA. Pocket curettage with laser as an adjunct to conventional mechanical root surface treatment has been increasingly performed by general practitioners because of its ease of use. However, in spite of the widespread use of the Nd:YAG laser among general practitioners, there is still insufficient proof from scientific studies of the positive clinical effects of this laser (Table 5). Opinions differ as to the use of lasers in periodontal pockets. The American Academy of Periodontology does not recommend the use of laser curettage (3, 4) but the Academy of Laser Dentistry (ALD) approves the adjunctive use of lasers for curettage following conventional mechanical root debridement (32).

Based on the results of previous *in vitro* and *in vivo* studies, the Nd:YAG laser cannot achieve root surface debridement to a satisfactory degree, due to insufficient ability to remove calculus and distinct root surface alteration induced by heat generation during irradiation. If utilized, the Nd:YAG laser should be employed as an adjunct to conventional mechanical treatments, rather than as a primary instrument in the treatment of periodontal pockets. That is, the Nd:YAG laser should be used for curettage of periodontal pockets to remove infected granulation tissue and epithelial lining as well as disinfection and detoxification of periodontal pockets, at a relatively low energy level, rather than debridement of calcified deposits and contaminated cementum at a high energy level, having the potential of producing thermal damages. Some clinical studies that used the Nd:YAG laser as a primary debriding instrument could not demonstrate the same or better clinical outcomes than with conventional SRP. There was insufficient calculus elimination as well as occasional inevitable thermal damages of root surface following Nd:YAG laser irradiation.

Many studies have reported that Nd:YAG laser irradiation produces unfavorable thermal changes on the root surface (30). However, variations in the manner and conditions of irradiation, such as energy output, use or nonuse of water irrigation, and the degree of contact tip angulation to the root surface, may produce different results. The root surface alterations following Nd:YAG laser irradiation for soft tissue curettage need to be reevaluated. Also, as soft tissue attachment to the root surface exposed to the Nd:YAG laser has not been reported *in vivo*, further investigations are necessary to histologically determine the tissue attachment to the Nd:YAG laser-treated root surface *in vivo*.

Regarding thermal influence, White et al. (207) examined *in vitro* the changes of intrapulpal temperatures during Nd:YAG laser irradiation at 0.3–3.0 W (30–150 mJ/pulse, 10 or 20 Hz) of root surfaces. They reported that, within the parameters outlined in their study, when pulsed Nd:YAG laser energy is applied to root surfaces with adequate remaining dentin thickness it should not cause devitalizing intrapulpal temperature rise.

Nonetheless, it is always necessary to bear in mind that, at a high energy level on oral tissues, the Nd:YAG laser will penetrate into deeper tissues of the target site. In particular, when the irradiation is directed perpendicular to the target, this deep penetration may occasionally cause unexpected thermal damage in the tooth pulp (196), alveolar bone, and other surrounding tissues. Spencer et al. (188) reported a mean temperature increase at the bone surface of 4.5–11.1 °C during Nd:YAG laser soft tissue surgery at high energy levels of 5–9 W (100–180 mJ/pulse, 50 Hz) with and without water coolant. Friesen et al. (60) reported a delayed healing response in bone tissue irradiated by Nd:YAG laser. Care must be taken when using the Nd:YAG laser, especially at a high energy level, in the treatment of periodontal pockets.

Further studies are needed to establish the use of this laser as an effective and safe treatment modality in nonsurgical periodontics, including repeated interventions of residual pockets after initial periodontal therapy and in the maintenance stage. Improved
treatment outcomes must be demonstrated with the adjunctive use of the Nd:YAG laser over those of conventional mechanical treatment alone, as well as suitable irradiation conditions and techniques.

### Er:YAG Laser

**Characteristics**

The Er:YAG laser was introduced in 1974 by Zharikov et al. (219) as a solid-state laser that generates a light with a wavelength of 2,940 nm. Of all lasers emitting in the near- and mid-infrared spectral range, the absorption of the Er:YAG laser in water is the greatest because its 2,940 nm wavelength coincides with the large absorption band for water. The absorption coefficient of water of the Er:YAG laser is theoretically 10,000 and 15,000–20,000 times higher than that of the CO2 and the Nd:YAG lasers, respectively (68, 155). Also, as part of the apatite component, OH groups show a relatively high absorption at 2,940 nm (44). Since the Er:YAG laser is well absorbed by all biological tissues that contain water molecules, this laser is indicated not only for the treatment of soft tissues but also for ablation of hard tissues (Fig. 6 and 7).

### Nd:YAG Laser – Clinical Studies on Periodontal Pocket Treatment

<table>
<thead>
<tr>
<th>Author and Year</th>
<th>References</th>
<th>Laser Parameters</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cobb et al. 1992</td>
<td>(29)</td>
<td>1.75–3 W 87.5–150 mJ/pulse, 20 Hz</td>
<td>Ineffective removal of calculus with thermal damage to the root surface, and decreased number of bacteria in periodontal pockets after laser treatment (Case series, 8 patients, 18 teeth)</td>
</tr>
<tr>
<td>Horton &amp; Lin 1992</td>
<td>(75)</td>
<td>2 W 100 mJ/pulse, 20 Hz* 2 min</td>
<td>Laser was equally or more effective than SRP in reducing or inhibiting recolonization of specific bacterial species for pocket treatment (CT, 15 patients, 45 segments)</td>
</tr>
<tr>
<td>Gold &amp; Vilardi 1994</td>
<td>(64)</td>
<td>1.25 and 1.75 W 62.5 and 87.5 mJ/pulse, 20 Hz</td>
<td>Laser removed pocket lining epithelium in periodontal pockets, without causing necrosis or carbonization of the underlying connective tissue (Case series, 6 patients, 24 specimens)</td>
</tr>
<tr>
<td>Ben Hatit et al. 1996</td>
<td>(22)</td>
<td>0.8–1.5 W 100 mJ/pulse, 8–15 Hz</td>
<td>SRP plus laser treatment showed more reduction of periodontopathic bacterial levels compared to SRP alone, but root surface alterations were observed after laser treatment (RCT, 14 patients, 150 sites)</td>
</tr>
<tr>
<td>Radvar et al. 1996</td>
<td>(145)</td>
<td>0.5 or 0.8 W 50 or 80 mJ/pulse, 10 Hz</td>
<td>No thermal damage of root surface, but no clinical or microbiological improvement after laser treatment compared to SRP (RCT, 11 patients, 80 sites)</td>
</tr>
<tr>
<td>Neil &amp; Mellonig 1997</td>
<td>(128)</td>
<td>2 W 80 mJ/pulse, 25 Hz</td>
<td>Similar reduction of probing depth was observed after SRP plus laser therapy and SRP alone, but SRP plus laser therapy showed significantly higher improvements in gingival index and gingival bleeding index (RCT in a split-mouth design, 10 patients, 186 teeth)</td>
</tr>
<tr>
<td>Liu et al. 1999</td>
<td>(109)</td>
<td>3 W 150 mJ/pulse, 20 Hz</td>
<td>Laser was less effective in reduction of crevicular IL-1β than traditional SRP (RCT in a split-mouth design, 8 patients, 52 sites)</td>
</tr>
<tr>
<td>Miyazaki et al. 2003</td>
<td>(119)</td>
<td>2 W 100 mJ/pulse, 20 Hz</td>
<td>Improvements regarding clinical parameters and subgingival microflora after Nd:YAG, CO2 and Ultrasonic treatments (RCT, 18 patients, 41 sites). Decrease of mean PD (NS between the 3 groups) Nd:YAG: from 6.50 ± 1.09 mm to 5.07 ± 0.83 mm (n = 14) CO2: from 6.92 ± 1.50 mm to 5.92 ± 1.93 mm (n = 13) Ultrasonic: from 6.86 ± 2.63 mm to 5.50 ± 2.06 mm (n = 14)</td>
</tr>
</tbody>
</table>

*Calculated from data presented in paper. SRP: scaling and root planing. CT: controlled trial. RCT: randomized controlled trial. PD: probing depth. NS: not significant.
Nagasawa (126), one of the pioneers in laser dentistry, demonstrated an approximately 3,000 nm absorption peak of enamel and dentin in the infrared spectral region. The absorption peak that Nagasawa found for dried dental hard substances was probably mainly due to absorption by intrinsic water in apatite crystals, and minimally due to OH groups of the mineral apatite (148). Kumazaki (107) speculated that, in the case of dental hard tissue, the Er:YAG laser is selectively absorbed by solid water and the hydration shell of hydroxyapatite, causing a collapse of apatite bindings.

In dentistry, the free-running pulsed Er:YAG laser has already been used clinically for caries removal and cavity preparation (34, 89, 92, 107, 115) and soft tissue treatment (14, 203). The FDA approved the pulsed Er:YAG laser for hard tissue treatment such as caries removal and cavity preparation in 1997 (193), unchanged for soft tissue surgery and sulcular debridement in 1999 and for osseous surgery in 2004.

The high absorption of the Er:YAG laser into water minimizes thermal influences on the surrounding tissues during irradiation. When the Er:YAG laser was used for an incision of pigskin in a noncontact mode, it showed formation of a thermally changed layer of only 10–50 µm (202). In the case of hard tissue procedures, some degree of heat generation is inevitable with the Er:YAG laser, since the Er:YAG laser emits in the infrared region and hard tissues have very low water content. However, the use of water coolant minimizes heat generation by cooling the irradiated area and absorbing excessive laser energy (26, 133, 201). In addition, a water spray facilitates hard tissue ablation by keeping the target moist (26). Er:YAG laser irradiation using water irrigation has been reported to produce an altered layer 5–15 µm in width on cementum and dentin surfaces (11, 12, 61).

The recently introduced Erbium, Chromium-doped: Yttrium-Scandium-Gallium-Garnet (Er,Cr:YSGG) laser with 2,780 nm wavelength and the Erbium-doped: Yttrium-Scandium-Gallium-Garnet (Er:YSGG) laser with 2,790 nm wavelength, which are more highly absorbed by OH ions than water molecules (44), are expected to have a performance similar to that of the Er:YAG laser.

**Mechanism of tissue ablation with the Er:YAG laser**

A mechanism of biological tissue ablation with the Er:YAG laser has been proposed, based on the optical properties of its emission wavelength and morphologic features of the surface ablated by Er:YAG laser. During Er:YAG laser irradiation, the laser

---

**Fig. 6. Photograph of the root surface after single pulse irradiation of the Er:YAG laser at various energy levels.** Single pulse Er:YAG laser irradiation was performed under water irrigation in a contact mode using a conventional cylindrical tip with a 600 µm diameter on the intact root surface at an energy density of 3.5, 7.1, 10.6, 17.7, 28.2, and 42.4 J/cm² per pulse (energy output of 10, 20, 30, 50, 80, and 120 mJ/pulse, respectively) starting from the upper left in the figure. The ablation defect became deeper according to the increase in energy output. The ablation defect shows chalky appearance without carbonization.

**Fig. 7. Scanning electron micrograph of the root surface after single pulse Er:YAG laser irradiation.** The irradiation was performed in a contact mode at an energy density of 42.4 J/cm² (energy output of 120 mJ/pulse) under water irrigation. The lased site shows crater-like ablation defect with a well defined edge and microstructured bottom, and without major crackings and thermal alterations. Original magnification: ×100. Bar = 100 µm.
energy is absorbed selectively by water molecules and hydrous organic components of the biological hard tissues and causes evaporation of water (photothermal evaporation). Further, in the case of hard tissue, the vapor produces an increase in the internal pressure leading to micro-explosions and consequent mechanical tissue collapse (thermomechanical or photomechanical ablation). The Er:YAG laser irradiation produces a very thin altered layer on the ablated surface, which consists of two distinct sub-layers: a superficial, significantly altered layer and a deeper, less affected (intermediate) layer. In the directly irradiated, superficial layer, micro-cracking, disorganization and slight recrystallization of the original apatites and reduction of surrounding organic matrix are evident after microexplosion, while the intermediate layer, which receives less energy, suffers mainly from the effects of energy accumulation, such as heat and subsequent microexplosion. The deep layer under the intermediate layer shows no change. W: water molecules. BA: biological apatites. PM: protein matrix. (Schema from Sasaki KM et al. Ultrastructural analysis of bone tissue irradiated by Er:YAG laser. Lasers Surg Med 2002: 31: 322-332; with permission. Lasers in Surgery and Medicine © copyright (2002) Wiley-Liss, Inc.).

Unlike CO2 laser (10,600 nm) irradiation, the Er:YAG laser is capable of ablating hard tissues. Koort et al. (97) reported that its effectiveness depends on the balance of absorption into water and hydroxyapatite (−PO4). Fried et al. (58, 59) suggested that the difference between the Er:YAG laser and CO2 laser collapse, resulting in a ‘thermomechanical’ or ‘photomechanical’ ablation (97). This phenomenon has also been referred to as ‘water-mediated explosive ablation’ (59, 180) (Fig. 8).

Fig. 8. Schematic view of hard tissue ablation by Er:YAG laser irradiation. During Er:YAG laser irradiation, the laser energy is absorbed selectively by water molecules and hydrous organic components of the biological hard tissues and causes evaporation of water (photothermal evaporation). Moreover, in hard tissue procedures, the water vapor production induces an increase of internal pressure within the tissue, resulting in explosive expansion called ‘microexplosion’ (71, 87). These dynamic effects cause mechanical tissue

- Before irradiation
- Er:YAG laser irradiation
- After irradiation
- Deep layer
- Intermediate layer
- Superficial layer
(10,600 nm) in the mechanism of enamel ablation is based primarily on the principal absorber in the hard tissue. He reported that primary absorption in water results in water-mediated ablation, and primary absorption in the bulk of enamel rods results in melting and vaporization. The absorption of the Er:YAG laser by inorganic components (hydroxyapatite) is much lower than that of the CO₂ laser (97). Thus, in the hard tissue ablation with the Er:YAG laser, the absorption into water and hydrous organic components rapidly occurs before heat accumulation caused by absorption into inorganic components takes place, resulting in thermo-mechanical, explosive ablation. The excellent ablation effect of the Er:YAG laser of both soft and hard tissues has received a lot of attention in the field of periodontal therapy, and has been extensively researched.

Basic studies

Removal of subgingival calculus: Dental calculus contains water in its structural micropores as well as in its intrinsic components. Since the Er:YAG laser has the ability to ablate dental hard tissues such as enamel and dentin, the laser was expected to be capable of removing dental calculus at much lower energy levels. Several researchers have already reported the promising ability of the Er:YAG laser to remove subgingival calculus in vitro (10, 12, 51, 55, 90, 91, 172, 191) (Table 6, Fig. 10, 11 and 12).

In 1994, Aoki et al. (10) first documented the ability of the Er:YAG laser to remove subgingival calculus in vitro. They showed that the pulsed Er:YAG laser used with water irrigation was capable of removing subgingival calculus from the root surface effectively at 30 ml/pulse (energy density of single pulse at the tip: 10.6 J/cm² per pulse) and 10 Hz, in the contact mode, directed perpendicular to the root surface using a conventional cylindrical contact tip 600 μm in diameter. In addition, ablation of the tooth substance following laser scaling was generally observed within cementum, with a slight rise in temperature of pulpal side during scaling. Their study suggested the potential for clinical application of the Er:YAG laser in subgingival scaling. Following the study, in 1995 Keller & Hibst (90) recommended that in contact irradiation perpendicular to the root surface under water irrigation, an energy level of 50 ml/pulse (tip diameter 600 μm, energy density 18 J/cm² per pulse) should be used for effective calculus removal to avoid damage to the cementum.

Soon after, Stock et al. (191) introduced a newly developed contact tip (chisel type) suitable for root surface treatment within periodontal pockets. They performed Er:YAG laser scaling at 120 ml/pulse (8 J/cm² per pulse) and 15 Hz with water spray and with the tip inclined at an angle of 20° to the root surface. They reported that only smooth ablation traces were visible in the cementum after Er:YAG laser scaling. Keller & Hibst (91) tried Er:YAG laser scaling at 120 and 150 ml/pulse (calculated energy density 15.0 and 18.8 J/cm² per pulse) and 10 and 15 Hz under water irrigation using the rotatable fiber tip with a chisel shaped profile (dimensions of the rectangular end: 0.5 × 1.6 mm), at 20 or 40° to the root surface (Fig. 9c). Calculus was effectively removed from the root surface without thermal alteration of the surface. Similarly, Folkwaczy et al. (51) and Frentzen et al. (55) reported that the Er:YAG laser scaling with water spray using a chisel tip resulted in complete or adequate calculus removal without thermal change of the root surface.

Aoki et al. (12) evaluated the effectiveness of Er:YAG laser scaling compared to conventional ultrasonic scaling. They performed laser scaling at 40 ml/pulse (14.2 J/cm² per pulse) and 10 Hz with water spray, using a conventional tip at 30° to the root surface in a sweeping motion. The level of calculus removal achieved by laser scaling was similar to that by ultrasonic scaling, although the laser scaling was slightly less efficient. Schwarz et al. (173) compared the degree of calculus removal with in vivo Er:YAG laser irradiation at 160 ml/pulse (energy output 120 ml/pulse and chisel tip size 1.65 × 0.5 mm; calculated energy density 14.5 J/cm² per pulse) and 10 Hz with removal after water spray or scaling and root planing with hand instruments. The study used roots of teeth that had been planned for extraction due to severe periodontal destruction. The laser treatment was performed in a coronal to apical direction in parallel paths, with the fiber tip inclined 15–20° to the root surface. The Er:YAG laser treatment provided selective subgingival calculus removal to a level equivalent to that provided by scaling and root planing.

Root substance removal during laser scaling: In a preliminary in vitro study, Aoki et al. (10) reported that the average depth of cementum ablation was approximately 40–136 μm following Er:YAG laser scaling in a straight line at 20–120 ml/pulse (7.1–42.4 J/cm² per pulse) and 10 Hz in perpendicular contact irradiation using a conventional tip. They later demonstrated that the depth of cementum ablation was generally 15–30 μm and occasionally reached 80 μm in localized areas exposing dentin surface, after in vitro Er:YAG laser scaling at 40 ml/pulse (14.2 J/cm² per pulse) and 10 Hz in oblique contact irradiation at 30° in a sweeping motion (12).
Stock et al. (191) reported that the maximum depth of ablation traces was approximately 100 μm after Er:YAG laser scaling at 120 mJ/pulse (8 J/cm² per pulse) and 15 Hz with water spray at 20° inclination of the chisel tip to the root surface. They also reported that the threshold for both calculus and cementum ablation was 0.8 J/cm². Folwaczny et al. (51) examined root substance removal while irradiating on root surfaces with or without calculus with the Er:YAG laser at 60–150 mJ/pulse (calculated energy density: 7.3–18.2 J/cm² per pulse) and 15 Hz with water spray using a chisel type contact tip (tip end 1.65 × 0.5 mm) in oblique contact irradiation at 30°. They observed that the root substance removal with the Er:YAG laser irradiation on the teeth without calculus was approximately 38, 70, 143, and 484 μm, respectively at 60 (7.3), 80 (9.7), 100 (12.2) and 150 mJ/pulse (18.2 J/cm² per pulse). They concluded that the root substance removal with the Er:YAG laser at lower energy densities up to 100 mJ/pulse (12.2 J/cm² per pulse) was comparable to that after conventional root surface instrumentation with curettes, and that selective calculus removal may be feasible using lower radiation energies.

However, Frentzen et al. (55) reported that, although Er:YAG laser scaling achieved complete debridement clinically, laser scaling at a panel setting of 160 mJ/pulse (output energy 100 or 120 mJ/pulse and calculated energy density 18.8 or 14.5 J/cm² per pulse in the use of chisel tip 1.1 × 0.5 mm or 1.65 × 0.5 mm, respectively) and 10 Hz with water spray resulted in an increased loss of cementum and dentin in vitro compared to mechanical scaling. They considered that this loss should be taken into

<table>
<thead>
<tr>
<th>Author and Year</th>
<th>References</th>
<th>Laser parameters</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aoki et al. 1994</td>
<td>(10)</td>
<td>10–120 mJ/pulse</td>
<td>Effective subgingival calculus removal at 10.6 J/cm² per pulse with little temperature increase and minimum cementum ablation</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(3.5–42.4 J/cm² per pulse)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 Hz, water irrigation</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° contact (round-end tip)</td>
<td></td>
</tr>
<tr>
<td>Keller &amp; Hibst 1995</td>
<td>(90)</td>
<td>50 ml/pulse (18 J/cm² per pulse), 1.5 or 3 Hz, water irrigation</td>
<td>Effective calculus removal at 18 J/cm² per pulse without greater damage to the cementum</td>
</tr>
<tr>
<td></td>
<td></td>
<td>90° contact (round-end tip)</td>
<td></td>
</tr>
<tr>
<td>Stock et al. 1996</td>
<td>(191)</td>
<td>120 ml/pulse (8 J/cm² per pulse)</td>
<td>Smooth ablation traces on the root surface after scaling with a new chisel-type contact tip</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 Hz, water spray</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20° contact (chisel tip)</td>
<td></td>
</tr>
<tr>
<td>Keller &amp; Hibst 1997</td>
<td>(91)</td>
<td>120 or 150 ml/pulse (15.0 or 18.8 J/cm² per pulse*)</td>
<td>Effective calculus removal with a chisel-type tip without thermal alteration of the root surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 or 15 Hz, water spray</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20 or 40° contact (chisel tip)</td>
<td></td>
</tr>
<tr>
<td>Aoki et al. 2000</td>
<td>(12)</td>
<td>40 ml/pulse (14.2 J/cm² per pulse)</td>
<td>Calculus removal ability comparable to ultrasonic scaling</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 Hz, water spray</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30° contact (round-end tip)</td>
<td></td>
</tr>
<tr>
<td>Folwaczny et al. 2000</td>
<td>(51)</td>
<td>60–150 ml/pulse (7.3–18.2 J/cm² per pulse*)</td>
<td>Complete calculus removal without thermal change of root surface</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15 Hz, water spray</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>30° contact (chisel tip)</td>
<td></td>
</tr>
<tr>
<td>Frentzen et al. 2002</td>
<td>(55)</td>
<td>100 or 120 ml/pulse (18.8 or 14.5 J/cm² per pulse*)</td>
<td>Clinically adequate debridement without carbonization or other side-effects of clinical relevance.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 Hz, water spray</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>20° contact (chisel tip)</td>
<td></td>
</tr>
<tr>
<td>Schwarz et al. 2003</td>
<td>(173)</td>
<td>120 ml/pulse (14.5 J/cm²*)</td>
<td>In vivo selective subgingival calculus removal to a level equivalent to that provided by scaling and root planing</td>
</tr>
<tr>
<td></td>
<td></td>
<td>10 Hz, water spray</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>15–20° contact (chisel tip)</td>
<td></td>
</tr>
</tbody>
</table>

*Calculated from data presented in paper and/or data obtained during personal communication with author.
account in the clinical situation. The crater depth of the treated root surface was approximately 40 and 80 μm with the use of tip 1.65 and 1.10, respectively. Regarding their results, Ishikawa (77) pointed out that Frentzen et al. employed a relatively high energy output for Er:YAG laser scaling, and commented that although the efficiency of laser scaling can be easily improved by using a higher output power, caution should be used when deciding on the power output, considering a balance of effectiveness and unnecessary tissue removal. Improvement of the effectiveness of laser scaling should rely on other variables, such as pulse repetition rate and pulse duration, rather than only on an increase of energy output.

Thus, the Er:YAG laser does not accomplish selective ablation of dental calculus in vitro, as the tissue underlying dental calculus is also removed during laser scaling (Table 7, Figs 11 and 12). For safe and effective clinical use, a combination of a higher pulse repetition rate and lower energy output is recommended in order to increase the efficiency of calculus ablation and simultaneously decrease the amount of cementum loss. With such irradiation conditions, the efficiency is improved without increasing the uncomfortable vibration stress experienced by patients. At the same time, selective calculus removal using the Er:YAG laser may be more feasible (12). Also, Folwaczny et al. (53) reported that the angulation of the application tip to the root surface has a strong influence on the amount of root substance removed during Er:YAG laser irradiation. The angulation of the application tip is another important factor for decreasing root substance removal.

Recently, Schwarz et al. (172) reported interesting findings. First, they performed in vivo Er:YAG laser scaling on periodontally diseased roots of teeth considered for extraction due to severe periodontal destruction, at panel settings of 120–180 mJ/pulse (energy output 71–106 mJ/pulse, calculated energy density 8.6–12.8 J/cm² per pulse) and 10 Hz using a
Aoki et al.

Fig. 10. Photographs of the root surfaces before and after Er:YAG laser scaling of subgingival calculus. Er:YAG laser scaling was performed in vitro at an energy density of 10.6 J/cm² per pulse (energy output of 60 mJ/pulse) and 30 Hz under water spray. The laser was applied using a chisel-type tip (1.4 × 0.45 mm) in contact mode, maintaining the tip oblique to the root surface at an angle of approximately 20°, and moving the tip in a back-and-forth motion. The time required for laser scaling was 112 s. Macroscopically, the laser-scaled area appears smooth and slightly chalky, but without any major thermal changes such as carbonization. a) Before laser scaling. b) After laser scaling. Part of the subgingival calculus was intentionally left on the edge of the treated root surface. Original magnification: × 25.
<table>
<thead>
<tr>
<th>Author and Year</th>
<th>References</th>
<th>Laser parameters</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aoki et al. 1994</td>
<td>(10)</td>
<td>10–120 mJ/pulse (3.5–42.4 J/cm² per pulse) 10 Hz, water irrigation 90° contact (round-end tip)</td>
<td>Chalky and micro-irregular appearance without melting and carbonization after laser scaling, and cementum ablation with a depth of 40–136 µm on average, following laser scaling in perpendicular contact irradiation in a straight line</td>
</tr>
<tr>
<td>Benthin et al. 1995</td>
<td>(23)</td>
<td>Er:YSGG 7.5–60 J/cm² 5 Hz, With and without water spray Noncontact</td>
<td>Reduction of <em>in vitro</em> fibroblast attachment after Er:YSGG laser irradiation on an intact root surface compared to attachment on a mechanically prepared surface</td>
</tr>
<tr>
<td>Stock et al. 1996</td>
<td>(191)</td>
<td>120 mJ/pulse (8 J/cm² per pulse) 15 Hz, water spray 20° contact (chisel tip)</td>
<td>A maximum root ablation of 100 µm after laser scaling</td>
</tr>
<tr>
<td>Israel et al. 1997</td>
<td>(80)</td>
<td>2.5–15 mJ/pulse 20 Hz, water spray Noncontact</td>
<td>An etched appearance with exposure of numerous tufts and/or fiber bundles of mineralized collagen as well as sharply defined microfractures of mineralized structure after irradiation</td>
</tr>
<tr>
<td>Fujii et al. 1998</td>
<td>(61)</td>
<td>75 mJ/pulse (26.5 J/cm² per pulse*) 1 pulse, water spray 90° contact (round-end tip)</td>
<td>Microstructured root surface with denaturation of collagen fibers up to a depth of 15 µm</td>
</tr>
<tr>
<td>Aoki et al. 2000</td>
<td>(12)</td>
<td>40 mJ/pulse (14.2 J/cm² per pulse) 10 Hz, water spray 30° contact (round-end tip)</td>
<td>Micro-irregular appearance and minimal change with characteristic staining of the lased root surface and 15–30 µm of cementum ablation</td>
</tr>
<tr>
<td>Folwaczny et al. 2000</td>
<td>(51)</td>
<td>60–150 mJ/pulse (7.3–18.2 J/cm² per pulse*) 15 Hz, water spray 30° contact (chisel tip)</td>
<td>Root substance removal comparable to conventional instrumentation and selective calculus ablation at lower energy level up to 100 mJ/pulse (12.2 J/cm² per pulse)</td>
</tr>
<tr>
<td>Folwaczny et al. 2001</td>
<td>(53)</td>
<td>60–180 mJ/pulse (7.3–21.8 J/cm² per pulse*) 10 Hz, water spray 15–90° contact (chisel tip)</td>
<td>Angulation of application tip to the root surface has a strong influence on the amount of root substance removed during laser irradiation.</td>
</tr>
<tr>
<td>Gašpirc &amp; Skalerič 2001</td>
<td>(63)</td>
<td>60–100 mJ/pulse (11.9–19.9 J/cm² per pulse*) 10 Hz, no water Noncontact</td>
<td>Influence on the morphology and diffusion process of root surfaces and no changes in the chemical structure of the root surface</td>
</tr>
<tr>
<td>Schwarz et al. 2001</td>
<td>(172)</td>
<td>71–106 mJ/pulse* (8.6–12.8 J/cm² per pulse*) 10 Hz, water spray 20° contact (chisel tip)</td>
<td>Smooth root surface morphology after laser scaling <em>in vivo</em> not comparable to the marked morphologic changes <em>in vitro</em></td>
</tr>
<tr>
<td>Frentzen et al. 2002</td>
<td>(55)</td>
<td>100 or 120 mJ/pulse (18.8 or 14.5 J/cm² per pulse*) 10 Hz, water spray 20° contact (chisel tip)</td>
<td>Increased loss of cementum and dentin compared to mechanical debridement</td>
</tr>
<tr>
<td>Sasaki et al. 2002</td>
<td>(164)</td>
<td>40 mJ/pulse (14.2 J/cm² per pulse*) 10 Hz, water spray 30° contact (round-end tip)</td>
<td>Slight melting with cluster formation of enlarged microparticles in cementum and dentin</td>
</tr>
<tr>
<td>Sasaki et al. 2002</td>
<td>(167)</td>
<td>40 mJ/pulse (14.2 J/cm² per pulse*) 10 Hz, water spray 30° contact (round-end tip)</td>
<td>No major compositional or chemically deleterious changes on the root surface except for reduction of organic components</td>
</tr>
</tbody>
</table>
exhibited an etched appearance with exposure of numerous tufts and/or fiber bundles of mineralized collagen as well as sharply defined microfractures of mineralized structure. Fujii et al. (61) showed a microstructured root surface with denaturation of collagen fibers up to a depth of 15 μm in cementum, following single-pulse, perpendicular contact Er:YAG laser irradiation at 75 mJ/pulse (calculated energy density: 26.5 J/cm² per pulse) under water spray.

Aoki et al. (12) reported that numerous rounded or sharp pointed projections were evident on the root surface after Er:YAG laser scaling with water spray, and that the superficial layer of the root surface ablated by Er:YAG laser irradiation presented minimal change with characteristic staining, and was subdivided histologically into two distinct layers: a superficial, significantly altered layer and an underlying, less affected (intermediate), layer. The superficial layer showed a fragile structure with micro-irregularities and degradation. They speculated that the deeply stained superficial layer is approaching ablation and is highly damaged, exhibiting both microstructural degradation and thermal denaturation, whereas the underlying subsurface layer is affected only by thermal denaturation, and is not degraded structurally.

Using FTIR spectroscopy analysis, Sasaki et al. (167) observed that the Er:YAG laser at 40 mJ/pulse (14.2 J/cm² per pulse) and 10 Hz used with water coolant did not cause major compositional changes or chemically deleterious changes in the root cementum and dentin. However, OH and amide bands related to organic components were significantly reduced compared to carbonate and phosphate bands related to inorganic components. Laser irradiation without water coolant produced slightly cyan-derived toxic substances. Gaspircˇ & Skalericˇ (63) reported that the Er:YAG laser at 60–100 mJ/pulse (calculated energy density 11.9–19.9 J/cm² per pulse) and 10 Hz influenced only the morphology and diffusion process of root surfaces but did not change the chemical structure of the root surface. Sasaki et al. (164) also reported that the surface lased by Er:YAG at 40 mJ/pulse (14.2 J/cm² per pulse) and 10 Hz under water irrigation showed slight melting with cluster formation of enlarged microparticles of inorganic components in scanning electron microscope observation at ultra-high magnification. The use of water spray during Er:YAG laser irradiation resulted in a cleaner and less porous surface. Thus, Er:YAG laser irradiation produces a characteristic microstructural change as well as minimal thermal damage on the treated root surface (Table 7, Fig. 11 and 12). On the other hand, Ishizaka et al. reported that a changed layer of maximum thickness 600 μm was detected in the dentin after cavity preparation with the Er:YAG laser at 80–140 mJ/pulse and 4 Hz using a fine water mist, as observed using polarizing and light microscopy (79). Folwaczny et al. (48) performed in situ Er:YAG laser irradiation in periodontal pockets of human corpses, at 60–100 mJ/pulse (calculated energy density 7.3–12.1 J/cm² per pulse) and 10 Hz (50 or 100 pulses) with water spray using a chisel type tip (1.65 × 0.5 mm) and reported that the

<table>
<thead>
<tr>
<th>Author and Year</th>
<th>References</th>
<th>Laser parameters</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Schoop et al. 2002</td>
<td>(169)</td>
<td>100 mJ/pulse (5.98 J/cm²)</td>
<td>Better conditions for fibroblast attachment after laser debridement</td>
</tr>
<tr>
<td>Feist et al. 2003</td>
<td>(46)</td>
<td>35 or 59 mJ/pulse (4.2 or 7.2 J/cm² per pulse*)</td>
<td>Faster adhesion and growth of fibroblasts on the surfaces treated with 35 mJ/pulse irradiation than those treated with either root planing or 59 mJ/pulse irradiation</td>
</tr>
<tr>
<td>Folwaczny et al. 2003</td>
<td>(48)</td>
<td>60–100 mJ/pulse (7.3–12.1 J/cm² per pulse*)</td>
<td>A deep semicircular area of thermal change with a depth of 255–611 μm in the root dentin close to the bottom of the pocket after laser irradiation in situ</td>
</tr>
<tr>
<td>Schwarz et al. 2003</td>
<td>(171)</td>
<td>120 mJ/pulse (14.5 J/cm² per pulse*)</td>
<td>Significantly greater cell attachment in vitro on the in vivo laser treated root than on the in vivo SRP treated root</td>
</tr>
</tbody>
</table>

*Calculated from data presented in paper and/or data obtained during personal communication with author. SRP: scaling and root planing.

Fig. 11. Photomicrograph of a histologic section of the root after Er:YAG laser scaling. Root surface was scaled in vitro using the Er:YAG laser at 14.2 J/cm² per pulse (40 ml/pulse) and 10 Hz under water spray with a conventional cylindrical tip contacted obliquely to the root surface at an angle of 30°. The treated surface generally shows microirregularity due to the ablation of the superficial part of the cementum layer. Minimal change with deep staining and microirregularities are noted on the lased surface. SC: subgingival calculus that was intentionally left on the edge of the treated root surface, and the border of the scaled area clearly indicated. C: cementum. CDJ: cementodental junction. D: dentin. Bar = 50 μm. (Photograph from Aoki A et al. In vitro evaluation of Er:YAG laser scaling of subgingival calculus in comparison with ultrasonic scaling. J Periodontal Res 2000: 35: 5: 266-277; with permission. Journal of Periodontal Research © copyright (2000) Blackwell Munksgaard, Inc.)

Fig. 12. Scanning electron micrograph of the root surface scaled by Er:YAG laser, at high magnification. Er:YAG laser scaling was performed in vitro at 14.2 J/cm² per pulse (40 ml/pulse) and 10 Hz with water spray using a conventional cylindrical tip contacted obliquely to the root surface at an angle of 30° in a sweeping motion. The laser-treated surface shows a characteristic microstructured appearance. Numerous rounded projections are evident on the lased root surface. Original magnification: × 1,000. Bar = 10 μm. (Photograph from Aoki A et al. In vitro evaluation of Er:YAG laser scaling of subgingival calculus in comparison with ultrasonic scaling. J Periodontal Res 2000: 35: 5: 266-277; with permission. Journal of Periodontal Research © copyright (2000) Blackwell Munksgaard, Inc.)

Studies that employed periodontally diseased root surfaces showed better results. Schoop et al. (169) reported that the surface structure of periodontally diseased root after Er:YAG laser irradiation at 100 ml/pulse (energy density 5.98 J/cm²) and 15 Hz with water spray offered better conditions for the adherence of fibroblasts in vitro than a root surface after mechanical scaling only. Schwarz et al. (171) performed in vivo Er:YAG laser irradiation at the panel setting of 160 ml/pulse (energy output 120 ml/pulse and chisel tip size 1.65 × 0.5 mm; calculated energy density 14.5 J/cm² per pulse) and 10 Hz with water spray or scaling and root planing with hand instruments on periodontally diseased roots of teeth considered for extraction due to severe periodontal destruction, and cultured fibroblasts on the treated teeth following extraction. They observed significantly greater cell attachment in vitro in the laser treatment group than in the SRP treatment group. Feist et al. (46) performed in vitro Er:YAG laser irradiation at the panel setting of 60 or 100 ml/pulse (energy output 35 or 59 ml/pulse and chisel tip size 1.65 × 0.5 mm; calculated energy density 4.2 or 7.2 J/cm² per pulse) and 10 Hz with water spray or scaling surfaces may result in decreased cell attachment on the treated surface, compared to mechanical treatment.
and root planing with curettes on periodontally diseased roots of teeth. They reported that the surfaces treated with 35 ml/pulse (4.2 J/cm² per pulse) Er:YAG laser irradiation promoted faster adhesion and growth than those treated with either root planing or 59 ml/pulse (7.2 J/cm² per pulse) Er:YAG laser irradiation. These better results may be due to the disinfection and detoxification effects of Er:YAG laser irradiation on the diseased root surface and absence of a smear layer on the treated root surface after irradiation, which are described later in this chapter.

Periodontal connective tissue attachment to the Er:YAG-lased root surface has not been fully studied yet. Further in vitro and animal experiments are required to clarify the biocompatibility of the root surface prepared by Er:YAG laser. In addition, whether supplementary treatment, using chemical or mechanical methods, is required to remove the superficially altered layer of the lased root surface needs to be investigated histologically.

Thermal generation during Er:YAG laser treatment and its influence on the pulp tissue: When applying lasers for hard tissue ablation, thermal side-effects have been a major problem. Heat generation during laser irradiation often caused inflammation and necrosis of the pulp (6). Aoki et al. (10) demonstrated that the use of water coolant effectively prevented thermal generation during laser scaling without compromising the efficiency of laser scaling. They examined the temperature rise on the pulpal wall of proximal surfaces of mandibular incisors during Er:YAG laser scaling for 20 s with and without water coolant, at 30 ml/pulse (10.6 J/cm² per pulse) and 10 Hz, in contact mode, directed perpendicular to the root. They observed that the maximum temperature rise without water coolant was 39 °C in the root surface and 18.4 °C in the pulpal wall on average, whereas that with water coolant was 2.4 °C in the root surface and 0.8 °C in the pulpal wall (the mean thickness of root: 1.38 mm, experiment at room temperature). In another study, they observed the temperature rise on the pulpal wall of proximal surfaces of mandibular incisors during Er:YAG laser scaling with water coolant was 1.4 °C in the pulpal wall (the mean thickness of root: 1.30 mm, experiment at room temperature) (12). Keller et al. (91) reported that the maximum temperature increase of the pulpal side was 4 °K (4 °C) at 10 Hz or 5.5 °K (5.5 °C) at 15 Hz on average during Er:YAG laser scaling at 120 and 150 ml/pulse (calculated energy density 15.0 or 18.8 J/cm² per pulse) under water irrigation using a chisel type tip, with a tip inclination of 20 or 40° to the root surface. Thus, temperature elevation in the pulpal wall during Er:YAG laser scaling used with water coolant would be limited within the physiologically tolerable level of pulp tissue (Table 8).

There are no histologic studies of pulp tissue response after Er:YAG laser scaling of subgingival calculus. However, regarding the pulpal response after cavity preparation with the Er:YAG laser at high energy levels, in vivo reports have indicated minimal thermal effects of the Er:YAG laser on pulp tissue (88, 213). Comparative studies of pulpal reactions after cavity preparation with the Er:YAG laser and those with the conventional high-speed bur have shown that pulpal responses induced by Er:YAG laser treatment with water coolant were acceptable, and that no histopathologic differences were observed between Er:YAG laser treatment and high-speed bur cutting (181, 186).

Thus, in animal studies, no major damage has been reported to occur in the pulp tissue after cavity preparation with Er:YAG laser using much higher energy levels than those employed in laser scaling. We observed no thermal effects on the pulp tissue following Er:YAG laser scaling of supragingival calculus in an experiment in dogs (unpublished data). Therefore, it may be presumed that Er:YAG laser subgingival scaling at a low energy level, especially with the contact tip directed obliquely or parallel to the root surface, does not produce any major deleterious outcomes in the pulp tissue.

Disinfection and detoxification: The Er:YAG laser may offer several antimicrobial advantages over conventional mechanical scaling, due to its beneficial properties such as bactericidal effect (9, 50), degradation and removal of bacterial endotoxins (192, 216), and ablation effects without producing a smear layer (194) (Table 8).

Ando et al. (9) reported that the Er:YAG laser exhibits a high bactericidal potential against periodontopathogenic bacteria such as P. gingivalis and Actinobacillus actinomycetemcomitans at a low energy level of 0.3 J/cm², and significant reduction of viable bacteria was observed in a P. gingivalis colony of diameter 0.8 mm after single pulse irradiation at above 7.1 J/cm². Folwaczny et al. (50) reported that Er:YAG laser irradiation at 60 ml/pulse (10 J/cm² per pulse) and 15 Hz causes reduction in bacteria on root surfaces in vitro. However, they noted that complete elimination of bacteria could not be achieved in their study.

Yamaguchi et al. (216) showed in vitro that the infrared spectrum of bacterial lipopolysaccharide had a peak at 2,940 nm, which also corresponded to the
wavelength of the Er:YAG laser, and that the Er:YAG laser at 100 mJ/pulse and 1 Hz (35.4 mJ/cm²) could effectively and rapidly remove most of the lipopolysaccharide that had been coated on the extracted root surfaces. Sugi et al. (192) reported that the amount of endotoxin on the diseased root surface treated by Er:YAG laser at 30 mJ/pulse (16.1 J/cm² per pulse) and 10 Hz under water spray was significantly less than that on the control diseased root surface from which calculus was removed by hand scaler, without damaging the underlying cementum. Also, Sasaki et al. (167) reported that root cementum and dentin treated with the Er:YAG laser used with water coolant was free of toxic substances such as cyanate (NCO⁻) and cyanamide (NCN₂⁻) that were observed on surfaces irradiated by CO₂ and Nd:YAG lasers. Thus, improved disinfection and detoxification may be expected on the Er:YAG laser-treated root surface.

### Clinical studies

Based on the results of in vitro studies, Watanabe et al. (203) performed clinical application of Er:YAG laser scaling in 1996. The laser scaling was carried out under water coolant at a panel setting of approximately 40 mJ/pulse on average (calculated energy output: 32 mJ/pulse, calculated energy density: 11.3 J/cm² per pulse), 10 Hz, using a straight contact tip (600 μm diameter), targeting the supra- and subgingival calculus on the root surface of 60 teeth in 60 patients. They reported that the Er:YAG laser could remove calculus from root surfaces in 95% of cases. Although scaled sites showed some irregularity, this was not clinically significant in 98% of cases, and reduction of pocket depth was obtained. Only a few patients complained about the unpleasant sound and vibration. There were no complications or side-effects during this clinical trial. Watanabe et al. suggested that laser scaling was safe and effective, and clinically useful.

Recently, Schwarz et al. (176) reported interesting clinical data of nonsurgical periodontal treatment, comparing Er:YAG laser irradiation with conventional scaling and root planing in a randomized, controlled clinical study using a split-mouth design in 20 patients. Periodontal pockets of 110 teeth having subgingival calculus with moderate to advanced periodontal destruction were treated under local anesthesia with either the Er:YAG laser or scaling and...
root planing using hand instruments. Er:YAG laser treatment was performed using chisel type contact tips (1.10 × 0.5 mm, or 1.65 × 0.5 mm) at the panel setting of 160 mJ/pulse (energy output 100 and 120 mJ/pulse and energy density 18.8 and 14.5 J/cm² per pulse for size 1.10 and 1.65 tip, respectively) and 10 Hz with water coolant. The laser treatment was performed in a coronal to apical direction in parallel paths, with an inclination of the fiber tip at 15–20° to the root surface. The laser treatment required less time than the scaling and root planing treatment. At a 6-month post-treatment evaluation, the laser treatment showed similar or better results than the scaling and root planing treatment in terms of reduction of bleeding on probing, pocket depth, and clinical attachment level. In particular, the laser group presented a significantly higher reduction of bleeding on probing and improvement of clinical attachment level compared to the scaling and root planing group. Furthermore, the difference between laser and hand instrumentation in treatment outcomes was much more significant in deeper pockets. The researchers concluded that the Er:YAG laser may present a suitable alternative to conventional mechanical debridement in nonsurgical periodontal treatment. Schwarz et al. (174) also reported that the clinical attachment gain obtained following Er:YAG laser nonsurgical periodontal treatment was maintained over a 2-year period.

Schwarz et al. (175) also investigated the necessity of adjunctive scaling and root planing after Er:YAG laser treatment. They performed a clinical study similar to the above-mentioned study (176), and found no additional improvement in clinical outcomes for the laser treatment followed by scaling and root planing compared to laser treatment alone. Schwarz et al. (172) previously showed that the clinical use of the Er:YAG laser resulted in a smooth root surface morphology without marked morphologic changes, and suggested that calculus removal can be selectively done in vivo. Based on these findings, it appears that in vivo Er:YAG laser treatment, as per their method, results in a root surface favorable for tissue attachment, without producing a typical microstructured root surface, and therefore without requiring additional scaling and root planing.

Most recently, Sculean et al. (179) compared the effectiveness of an Er:YAG laser to that of ultrasonic scaler for nonsurgical periodontal treatment. Twenty patients with moderate to advanced periodontal destruction were randomly treated in a split-mouth design with a single episode of subgingival debride-ment using either an Er:YAG laser device (energy output 120 mJ/pulse; energy density 14.5 J/cm² per pulse; 10 Hz) combined with a calculus detection system with fluorescence induced by 655 nm InGaAsP diode laser radiation, or an ultrasonic instrument. Six months following treatment, there was a statistically significant improvement in the mean values of bleeding on probing, probing pocket depth, and clinical attachment level in both groups. However, no statistically or clinically significant differences were observed between the treatment modalities.

Summary of clinical application of the Er:YAG laser

Research conducted so far has indicated the safety and effectiveness of clinical application of the Er:YAG laser for periodontal pocket treatment, including root surface debridement. Er:YAG laser irradiation may be a promising, useful adjunctive or alternative method to the conventional technique for root preparation and pocket curettage (Table 9, Fig. 13 and 14). However, the effects of the Er:YAG laser need to be demonstrated in further randomized controlled trials and a subsequent meta-analysis.

With respect to healing after Er:YAG laser scaling, no histologic studies have been reported. Although uneventful clinical wound healing has been reported after periodontal treatment using the Er:YAG laser, minimal thermal changes have been reported after Er:YAG laser irradiation on both hard and soft tissue. Therefore, further studies are necessary to clarify the histologic attachment of periodontal tissues to the irradiated root surface in vivo.

The Er:YAG laser has some shortcomings when used for subgingival scaling. For clinical application in periodontal pockets where the operator cannot visualize the irradiated target, special tips should be designed to facilitate insertion into the periodontal pocket and detection of the presence of dental calculus on the surface (91, 205) (Fig. 9). Also, since Er:YAG laser irradiation causes splashing of water and blood from pockets as a result of explosive ablation, adequate high speed evacuation by means of not only an intraoral suction but also an extraoral evacuation apparatus is required to prevent contamination by blood and water splattering.

Recently, as a novel application of laser, the use of diode laser fluorescence spectroscopy for detection of dental calculus has been suggested by Hibst et al. (74). Keller et al. (93) reported a novel method of subgingival root cleaning with the Er:YAG laser combined with diode laser fluorescence spectroscopy, and this work has already resulted in the
<table>
<thead>
<tr>
<th>Author and Year</th>
<th>Reference</th>
<th>Laser parameters</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Watanabe et al. 1996</td>
<td>(203)</td>
<td>Approximately 32 mJ/pulse* (panel setting: approximately 40 mJ/pulse on average) (11.3 J/cm² per pulse*) 10 Hz, water spray oblique contact round-end tip (600 µm in diameter)</td>
<td>Safe and effective calculus removal and subsequent pocket depth reduction at 4 weeks Case series, 60 patients, 60 sites of 60 teeth Removal of supragingival calculus (n = 25): Decrease of mean RD: from 2.9 ± 1.3 mm to 2.5 ± 1.4 mm Removal of subgingival calculus (n = 35): Decrease of mean PD: from 5.6 ± 2.0 mm to 2.6 ± 0.9 mm</td>
</tr>
<tr>
<td>Schwarz et al. 2001</td>
<td>(176)</td>
<td>100 or 120 mJ/pulse* (panel setting: 160 mJ/pulse) (18.8 or 14.5 J/cm² per pulse*) 10 Hz, water spray 15–20° contact chisel tip (rectangular end: 1.10 × 0.5 or 1.65 × 0.5 mm)</td>
<td>Similar or better improvement of clinical parameters at 6 months after pocket treatment with the laser, compared to SRP treatment (RCT in a split-mouth design, 20 patients, 660 sites of 110 teeth in total) Decrease of mean BOP(+) score (P &lt; 0.05 between the 2 groups): Laser group: from 56% to 13% SRP group: from 52% to 23% Decrease of mean PD (NS between the 2 groups): Laser group: from 4.9 ± 0.7 mm to 2.9 ± 0.6 mm SRP group: from 5.0 ± 0.6 mm to 3.4 ± 0.7 mm Decrease of mean CAL (P &lt; 0.001 between the 2 groups): Laser group: from 6.3 ± 1.1 mm to 4.4 ± 1.0 mm SRP group: from 6.5 ± 1.0 mm to 5.5 ± 1.0 mm</td>
</tr>
<tr>
<td>Schwarz et al. 2003</td>
<td>(174)</td>
<td>100 or 120 mJ/pulse* (panel setting: 160 mJ/pulse) (18.8 or 14.5 J/cm² per pulse*) 10 Hz, water spray 15–20° contact chisel tip (rectangular end: 1.10 × 0.5 or 1.65 × 0.5 mm)</td>
<td>Maintained improved clinical parameters of periodontal pockets after 2 years for both laser and SRP treatments (RCT in a split-mouth design, 20 patients, 660 sites of 110 teeth in total) Decrease of mean CAL (P &lt; 0.001 between baseline and 1 year/2 years, and NS between 1 and 2 years, for both groups): Laser group: from 6.3 ± 1.1 mm to 4.5 ± 0.4 mm at 1 year and to 4.9 ± 0.4 mm at 2 years SRP group: from 6.5 ± 1.0 mm to 5.6 ± 0.4 mm at 1 year and to 5.8 ± 0.4 mm at 2 years</td>
</tr>
<tr>
<td>Schwarz et al. 2003</td>
<td>(175)</td>
<td>100 or 120 mJ/pulse* (panel setting: 160 mJ/pulse) (18.8 or 14.5 J/cm² per pulse*) 10 Hz, water spray 15–20° contact chisel tip (rectangular end: 1.10 × 0.5 or 1.65 × 0.5 mm)</td>
<td>No additional improvement in the clinical parameters at 12 months after pocket treatment with the laser + SRP treatment, compared to laser treatment alone (RCT in a split-mouth design, 20 patients, 600 sites of 100 teeth in total) Decrease of mean PD (NS between the 2 groups): Laser + SRP group: from 5.2 ± 0.8 mm to 3.2 ± 0.8 mm Laser group: from 5.0 ± 0.7 mm to 3.3 ± 0.7 mm Decrease of mean CAL (NS between the 2 groups): Laser + SRP group: from 6.9 ± 1.0 mm to 5.3 ± 1.0 mm Laser group: from 6.6 ± 1.1 mm to 5.0 ± 0.7 mm</td>
</tr>
</tbody>
</table>

*Calculated from data presented in paper and/or data obtained during personal communication with author. PD: probing depth. SRP: scaling and root planing. RCT: randomized controlled trial. BOP: bleeding on probing. CAL: clinical attachment level. NS: not significant.
development of a commercial device (179). Er:YAG laser treatment combined with an automatic calculus-detecting system may be a novel technical modality for pocket therapy in the near future.

In addition, with the Er:YAG laser, the results of studies should include a description of the energy density (fluence) per pulse at the end of contact tip, since the size and shape of the contact tip varies among the laser apparatuses.

**Diode lasers**

**Characteristics**

The diode laser is a solid-state semiconductor laser that typically uses a combination of Gallium (Ga), Arsenide (Ar), and other elements such as Aluminum (Al) and Indium (In) to change electrical energy into light energy. The wavelength range is about 800–980 nm. The laser is emitted in continuous-wave and gated-pulsed modes, and is usually operated in a contact method using a flexible fiber optic delivery system. Laser light at 800–980 nm is poorly absorbed in water, but highly absorbed in hemoglobin and other pigments (7). Since the diode basically does not interact with dental hard tissues, the laser is an excellent soft tissue surgical laser (156), indicated for cutting and coagulating gingiva and oral mucosa, and for soft tissue curettage or sulcular debridement. The FDA approved oral soft tissue surgery in 1995 and sulcular debridement in 1998 by means of a diode laser (GaAlAs 810 nm).

The diode laser exhibits thermal effects using the ‘hot-tip’ effect caused by heat accumulation at the end of the fiber, and produces a relatively thick coagulation layer on the treated surface (7). The usage is quite similar to electrocauterization. Tissue penetration of a diode laser is less than that of the Nd:YAG laser, while the rate of heat generation is higher (147), resulting in deeper coagulation and more charring on the surface compared to the Nd:YAG laser. The width of the coagulation layer was reported to be in excess of 1.0 mm in an incision of bovine oral soft tissue *in vitro* (208). The advantages of diode lasers are the smaller size of the units as well as the lower financial costs.

**Basic studies**

Concerning the effects on the root surface, Kreisler et al. (106) examined the periodontal ligament cell attachment to the 810 nm diode laser-treated root surface. After scaling and root planing the periodontally diseased root surface with curettes followed by air-powder abrasive treatment, the laser group received diode laser irradiation at 1 W in the continuous wave mode for 20 s and the control group was left unirradiated. There was no significant difference between the laser and the control groups in cell attachment. This finding suggested that the diode laser did not produce any deleterious effect on the root surface. Thus, it is generally considered that diode laser surgery can be performed safely in close proximity to dental hard tissue.
However, Kreisler et al. (99) further evaluated possible morphologic alterations of the root surfaces with a human blood film after noncontact GaAlAs-diode laser (809 nm) irradiation (0.5–2.5 W, continuous wave, 10–30 s). Interestingly, they reported that lasing dry or saline-moistened root specimens resulted in no detectable alterations; however, the blood-coated specimens showed severe damage depending on the irradiation conditions. Irradiation at 1 W and below had barely any negative effect on the root surface, whereas irradiation at 1.5 W and higher resulted in partial or total carbonization. Kreisler et al. (101) also examined intrapulpal temperature elevations during diode laser (809 nm GaAlAs) irradiation on the root surface, performing laser irradiation at 0.5–2.5 W in the continuous wave mode for 120 s. Temperature elevations between 0.5 and 32.0 °C were registered in an energy- and time-dependent manner. They reported the risk of temperature elevation of the pulpal side during diode laser irradiation on the root surface. Schwarz et al. (173) performed \textit{in vivo} GaAlAs diode laser treatment (810 nm, 1.8 W, pulsed, pulse/pause relation 1 : 10) on periodontally diseased roots of teeth considered for extraction due to severe periodontal destruction and examined the degree of calculus removal after extraction. They reported that diode laser was unsuitable for

Fig. 14. Clinical application of Er:YAG laser for the treatment of periodontal pocket. Subgingival curettage in combination with gingivectomy was performed using Er:YAG laser, to treat a periodontal pocket having gingival enlargement at the buccal side of a maxillary left canine with a porcelain-fused metal crown. The lesion did not successfully improve after repeated conventional mechanical debridements using curettes and ultrasonic scaler. First, marginal gingiva, approximately 2 mm wide, was removed with the Er:YAG laser at an energy density of 10.6 J/cm² per pulse (energy output 30 mJ/pulse) and 10 Hz under local anesthesia. The gingiva was easily resected with minimal bleeding. Then, subgingival curettage was performed with the laser in contact mode using a conventional cylindrical contact tip with a tapered end (Fig. 9b) which enables lateral irradiation, keeping the tip parallel to the gingival wall within the periodontal pocket. Diseased granulation tissues were effectively removed by laser without any major thermal damage and with minimal bleeding. The patient did not experience any stress and vibration during irradiation, and did not complain of any postoperative pain or discomfort. a) Before laser treatment. The mid-buccal site was 5 mm deep and positive for bleeding on probing (BOP). b) Immediately after treatment. c) One week after treatment. The wound healing was uneventful and favorable. d) Nine months after treatment. The periodontal pocket improved and pocket depth reduced to 1 mm with no BOP and without unaesthetic exposure of root surface due to marked gingival recession.

Lasers in nonsurgical periodontal therapy
calculus removal and altered the root surface in an undesirable manner.

Thus, diode lasers at a high energy level, especially in a continuous mode, can cause root surface alterations in the presence of blood and elevated temperatures, depending on the power employed.

Clinical studies

Some studies have demonstrated that a diode laser facilitated bacterial elimination from periodontal pockets, resulting in better healing. Moritz et al. (121) reported pocket irradiation with a diode laser (805 nm) following scaling. Irradiation with the diode laser at a power output of 2.5 W in pulsed mode (50 Hz, pulse duration 10 ms), produced considerable bacterial elimination from periodontal pockets at a much higher level than the scaling alone group, especially in terms of A. actinomycomitans. Moritz et al. (122) also performed a clinical study using a diode laser (805 nm) as an adjunctive treatment for periodontal pockets in order to reduce or eliminate bacteria. The pulsed irradiation at 2.5 W (50 Hz, pulse duration 10 ms) was performed three times 1 week, 2 months, and 4 months after scaling, while the control group was rinsed with H$_2$O$_2$. After 6 months, the bacterial reduction in the laser therapy group was significantly higher than in the control group. The improvement of bleeding on probing scores and pocket depths were greater in the laser group. They concluded that diode laser therapy, in combination with scaling, supports healing of periodontal pockets by eliminating bacteria (Table 10).

Regarding clinical use of the diode laser for pocket treatment, Coluzzi (33) recommended laser soft tissue curettage at 0.4 W in continuous wave mode after mechanical debridement of root surface, followed by irradiation at 0.6 W for hemostasis and bacterial reduction, while Gutknecht et al. (67) suggested the use of a diode laser at 2 W in continuous wave mode for curettage before mechanical debridement. Further detailed studies are required to establish proper irradiation conditions, including the use of water coolant, for periodontal pocket therapy with diode lasers.

Other applications

Hibst et al. (73, 74) developed a novel laser device for caries detection (Diagnodent®, KaVo, Biberach, Germany), which uses laser fluorescence induced by the 655 nm InGaAsP diode laser. It was suggested that caries-associated bacteria or their byproducts might be the source of reaction to the increasing fluorescence (44, 96). Hibst et al. (74) identified the source of red excited fluorescence present in caries lesions as porphyrins, especially proto-porphyrin IX, which are products of oral bacteria, such as Prevotella intermedia and P. gingivalis. They also suggested another application of laser fluorescence for calculus detection (74, 163). Recently, the 655 nm diode laser system has been reported to be useful for detection of

<table>
<thead>
<tr>
<th>Author and Year</th>
<th>References</th>
<th>Laser parameters</th>
<th>Findings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Moritz et al. 1997</td>
<td>(121)</td>
<td>2.5 W, 50 Hz 805 nm</td>
<td>Bacterial elimination from periodontal pockets at a much higher level than scaling alone group</td>
</tr>
<tr>
<td>Moritz et al. 1998</td>
<td>(122)</td>
<td>2.5 W, 50 Hz 805 nm</td>
<td>Diode laser therapy in combination with scaling supports healing of periodontal pockets by eliminating bacteria</td>
</tr>
<tr>
<td>Kreisler et al. 2001</td>
<td>(106)</td>
<td>1 W, CW 810 nm</td>
<td>No significant difference in the cell attachment to the root surface between laser treatment and the control groups</td>
</tr>
<tr>
<td>Kreisler et al. 2002</td>
<td>(99)</td>
<td>0.5–2.5 W, CW 809 nm</td>
<td>Dry or saline-moistened root specimens resulted in no detectable alterations; however, blood-coated specimens showed severe damage depending on the irradiation conditions</td>
</tr>
<tr>
<td>Kreisler et al. 2002</td>
<td>(101)</td>
<td>0.5–2.5 W, CW 809 nm</td>
<td>Risk of temperature elevation of pulpal side during diode laser irradiation on the root surface</td>
</tr>
<tr>
<td>Schwarz et al. 2003</td>
<td>(173)</td>
<td>1.8 W, Pulsed 810 nm</td>
<td>Diode laser was ineffective for calculus removal, and caused alteration of root surface such as grooves and crater-like defects in vivo</td>
</tr>
</tbody>
</table>

CW: continuous wave.
calculus that includes a significant amount of bacteria or their byproducts.

Keller et al. (93) reported that the degree of root debridement can be assessed by laser fluorescence and that subgingival root cleaning with the Er:YAG laser can be optimized with the aid of laser fluorescence spectroscopy. An apparatus combining the Er:YAG laser with the diode laser fluorescence for root surface preparation is already being marketed. Folwaczny et al. (49) also reported that subgingival calculus can be reliably detected in vitro using laser fluorescence induced by 655 nm InGaAsP diode laser. Krause et al. (98) observed that laser fluorescence values decreased significantly after in vitro scaling of extracted teeth, and the values were strongly correlated with the presence of calculus. Schwarz et al. (173) reported that the Er:YAG laser, combined with a calculus detection system with fluorescence induced by 655 nm InGaAsP diode laser, provided selective subgingival calculus removal to a level equivalent to that provided by scaling and root planing.

Traditionally, calculus detection has been performed manually by judging the ruggedness of the root surface using a periodontal probe. The laser fluorescence probe may be a novel, valuable tool for clinical detection of calculus in the near future.

**Argon laser**

**Characteristics**

The argon laser uses argon ion gas as an active medium and is fiber optically delivered in continuous wave and gated pulsed modes. This laser has two wavelengths, 488 nm (blue) and 514 nm (blue-green), in the spectrum of visible light. The argon laser is poorly absorbed in water and therefore does not interact with dental hard tissues. However, it is well absorbed in pigmented tissues, including hemoglobin and melanin, and in pigmented bacteria. Although not widely used in periodontal therapy, in operative dentistry the 488 nm argon laser is commonly used for curing composite resin (142) and bleaching teeth in the dental office, and the application for caries prevention has also been studied (127). The argon laser was approved by the FDA for oral soft tissue surgery and curing of composite materials in 1991 and for tooth whitening in 1995 (193).

**Basic and clinical studies**

Henry et al. (69, 70) reported that the argon laser at a low level has a bactericidal effect on the *Prevotella* and *Porphyromonas* species in the presence of oxygen. They suggested that low doses of argon laser radiation may be effective in the treatment of clinical infections caused by biofilm-associated species of *Prevotella* and *Porphyromonas*. In a clinical study, Finkbeiner (47) treated a total of 1,328 pockets from 30 patients, with argon laser pocket thermolysis in combination with mechanical root planing. Argon laser treatment was performed using a 300-μm fiber in contact at 0.4 W, for 20–30 s per pocket, with coaxial irrigation. He reported that the 4–5 mm pockets were reduced by a mean of 1.62 mm, the 6–7 mm pockets by 2.85 mm, and the 8–9 mm pockets by 3.30 mm.

Considering the advantages of eradication of pigmented bacteria, this laser may be useful for the treatment of periodontal pockets. Further in vitro and in vivo studies are required to demonstrate the clinical benefits of this laser.

**Alexandrite laser**

The Alexandrite laser is a solid-state laser employing a gemstone called Alexandrite, which is chromium-doped:Beryllium-Aluminum-Oxide chrysoberyl (Cr⁺³; BeAl₂O₄) and is one of the few trichroic minerals. In 1995 Rechmann & Henning (149) first reported that the frequency-doubled Alexandrite laser (wavelength 337 nm, pulse duration 100 ns, double spikes, q-switched) could remove dental calculus in a completely selective mode without ablating the underlying enamel or cementum. Based on the difference in spectral region of fluorescence emission from dentin and that from subgingival calculus, they assumed that the wavelength of the Alexandrite laser may be favorable for selective calculus ablation (149, 150). Their studies revealed that the Alexandrite laser at the fluence of 1 J/cm² and pulse repetition rate of 55 Hz under water-cooling could selectively ablate supra- and subgingival calculus as well as dental plaque. This laser has a wavelength in the ultraviolet spectrum and therefore does not produce any morphologic damage to enamel surface or root cementum (151), although extremely slight compositional change such as minimal reduction of amide II band is detected in the lased cementum by FTIR spectroscopy analysis (153). Rechmann et al. (152) also demonstrated that there was no pulpal damage after removal of calculus with the Alexandrite laser at 1.5–6 J/cm² and 70 Hz (pulse duration 1 μs) under water-cooling in dogs. However, the mechanism of selective ablation has not been clarified yet. The development of this laser for clinical use is widely
expected due to its excellent ability for selective calculus removal from the tooth or root surface without ablating the tooth structure. However, there is concern regarding use of light in the ultraviolet spectral region, and further studies are required to demonstrate the safety and effectiveness of this laser in clinical usage and to develop a laser apparatus appropriate for clinical use.

**Excimer lasers**

Excimer lasers are lasers that use a noble-gas halide, which is unstable, to generate radiation, usually in the ultraviolet region of the spectrum. Excimer laser wavelength depends on the chemical component serving as the medium of the laser. It has been suggested that tissue ablation occurs in the nonthermal process of photoablation, likely due to an instantaneous increase of the temperature or a straight combination of chemical elements (57).

In an *in vitro* experiment, Frentzen et al. (57) demonstrated that the ArF excimer laser, wavelength 193 nm, could effectively remove dental calculus without causing any damage to the underlying surface. The cementum surface was clean, and only a slight roughness could be observed after irradiation, supporting the use of excimer lasers for laser scaling. Folwaczny et al. (52) have reported that the 308 nm wavelength XeCl excimer laser could effectively ablate dental calculus without thermal damages or smear layer production.

Recently, flexible quartz glass fibers for XeCl-exci- mer laser delivery systems have become available. However, apparatus cost and size still constitute an obstacle for clinical application of these lasers. Furthermore, ultraviolet rays should be used with caution, as they may have deleterious effects on biological tissues.

### Application of lasers for the treatment of peri-implantitis

It is well known that adherent bacterial plaque and calculus develop on the surface of implant abutments, as in natural teeth. The maintenance treatment is required to keep the peri-implant tissue healthy in implant therapy. However, mechanical instruments such as metal curettes and ultrasonic scalers are prohibited for decontamination of titanium implant surfaces, since they easily damage the titanium surface.

Recently, lasers have been widely used for soft tissue incision in exposing submerged implants. Lasers may be used for decontamination of implant surface and treatment of peri-implantitis without damaging the implant surface (18). Regarding the effect of lasers on titanium, the Nd:YAG laser is not suitable for implant therapy, since it easily ablates the titanium irrespective of output energy. However, diode lasers basically do not interact with titanium or the coated material (24, 104, 158). As for the Er:YAG and CO₂ lasers, Kreisler et al. (104) suggested that the power output must be controlled so as to avoid damage of implant surfaces. Matsuyama et al. (116) also observed that the Er:YAG laser causes damage on the titanium surface at a high energy level, such as 100 ml/pulse (35.4 J/cm² per pulse), but does not result in any morphologic change or major temperature elevation at a low energy level under 50 ml/pulse (17.7 J/cm² per pulse) and 30 Hz, with water coolant, which is suitable for periodontal treatment. Schwarz et al. (177) observed that the Er:YAG laser at 100 ml/pulse (energy out put of 85 ml/pulse, calculated energy density 10.3 J/cm² per pulse) and 10 Hz under water irrigation does not damage titanium surfaces and does not affect the attachment of osteoblast-like cells. Their preliminary clinical results (178) have also shown that nonsurgical treatment of peri-implantitis with an Er:YAG laser at 100 ml/pulse and 10 Hz (energy density 12.7 J/cm² per pulse) under water spray led to a statistically significant reduction in pocket depth and gain in clinical attachment level.

Effective decontamination of the implant surface without excessive temperature elevation and any morphologic changes by CO₂ (energy density 286 J/cm² and 245 J/cm²) or Er:YAG (calculated energy density 26.2 or 52.4 J/cm² per pulse) lasers has been reported *in vitro* by Kato et al. (84) and Kreisler et al. (100, 105). However, the risk of moderate to high temperature elevation has been noted after CO₂ or diode laser irradiation (102, 132). Laser treatment of peri-implantitis may also be a promising field; however, further studies are required for application of lasers in implant maintenance therapy.

### Disadvantages and precautions in the clinical use of lasers

Lasers may be novel, effective tools for the treatment of periodontitis. However, lasers have disadvantages...
as well as advantages. Therefore, precautions should be taken when performing laser surgery (Table 11). The position paper of the American Academy of Periodontology suggests several important precautions in the use of lasers (4).

Laser light interacts with target tissues not only in the contact irradiation mode but also in the non-contact irradiation mode. Therefore, inadvertent irradiation to the patient’s eyes, throat, and delicate oral tissues outside the target site may occur during treatment and must be prevented (4). Particular care must be taken to avoid accidental irradiation to the eyes. The most important precaution in laser surgery is the use of glasses for eye protection. Before laser treatment, protective eyewear, specifically blocking the wavelength of the laser in use, must always be worn by patients, operator, and assistants (4). The laser beam may be reflected off shiny metal surfaces of dental instruments, such as retractors or mouth mirrors, which can cause accidental irradiation to adjacent tissues (4). Use of wet gauze packs may be occasionally useful for protection of the oral tissues surrounding the surgical site from accidental beam impact (138). Also, adequate high speed evacuation is necessary to capture the laser plume, which is a biohazard (4, 43). Contact with tooth enamel during periodontal treatment should be avoided during CO₂ and Er:YAG laser emission, as they easily cause melting or ablation.

There are few studies on the safety criteria for intraoral usage of lasers. With the Er:YAG laser, Aoki et al. (13) evaluated the effects of inadvertent irradiation on the tongue of rat. Er:YAG laser irradiation in a noncontact defocused mode caused no major damage to the tongue, especially when used with water irrigation. Although contact irradiation caused a tissue defect, thermal damage was rarely observed, and the healing process was without clinical problems. They concluded that inadvertent irradiation with the Er:YAG laser within the usual power setting used for dental treatment did not cause severe damage to surrounding soft tissues in the oral cavity.

There also exists a risk of excessive tissue destruction by direct ablation and thermal side-effects of periodontal tissues during irradiation into periodontal pockets. Improper use of lasers could cause further destruction of the intact attachment apparatus at the bottom of pockets as well as excessive ablation of root surface and gingival walls. Root surface with major thermal damage could render the tissue incompatible for normal cell attachment and healing. Thermal injury to the pulp tissue and underlying bone tissue would also be a concern with some lasers, especially with those exhibiting deep penetration. Therefore, thermal injury must be prevented by proper irradiation conditions and techniques.

Regarding the laser apparatus, development of a new laser system as well as improvement of currently available laser systems, such as miniaturization of device size and advances of performance, are required. Also, development of a new contact probe and handpiece suitable for periodontal treatment is necessary, as accessibility of contact probes into periodontal pockets is limited due to complex root morphology and furcated roots.

The high financial cost of the laser apparatus is still somewhat prohibitory, and this has prevented the spread of laser treatment among general practitioners. However, the price is expected to decrease with developments in laser technology and with increasing demand.

**Conclusions**

With conventional mechanical instruments, complete access and disinfection may not be achieved during the treatment of periodontal pockets. The effectiveness of instrumentation may vary with the skills and experience of the practitioner and is therefore
technique sensitive. Conventional mechanical treatment has various limitations in techniques and effects, and lasers have been introduced as an adjunctive or alternative tool for mechanical therapy.

Basically, lasers have the potential advantages of bactericidal effect, detoxification effect, and removal of the epithelium lining and granulation tissue, which are desirable properties for the treatment of periodontal pockets. Some lasers may be capable of effectively removing not only dental plaque but also calculus from the root surface with extremely low mechanical stress and no formation of a smear layer on the treated root surface. Furthermore, potential biostimulation effects of scattering and penetrating lasers on the cells surrounding the target tissue during irradiation might be helpful for the reduction of inflammation and healing of periodontal tissues. Considering the various advantages of laser irradiation, its use in combination with conventional mechanical treatment or alone has the potential to improve the condition of the periodontal pockets more than mechanical therapy alone.

Also, considering the evidence of bacterial invasion into the soft tissue of periodontal pockets (130, 161), not only debridement of the root surface but also removal of the epithelium lining and granulation tissue of the gingival wall within periodontal pockets could be important factors in the treatment of moderate to deep pockets in order to promote attachment of gingival connective tissue to the root surface. This might be particularly applicable to residual pockets, after initial therapy and during the maintenance period, that are not resolved by mechanical therapy alone. Lasers may be used to accomplish curettage of the soft tissue wall, and provide favorable conditions more effectively than the currently available instruments. Comprehensive treatment including preparation of both hard and soft tissue walls within pockets should be considered for more effective nonsurgical periodontal therapy in the future, and this is what may be accomplished by lasers. Thus, lasers could play an important role in comprehensive pocket therapy.

Based on the limited research so far, the Er:YAG laser holds promise as a useful tool to debride safely and effectively both the root surface and gingival tissue of the periodontal pockets, and the Nd:YAG, diode and Ar lasers have a potential for soft tissue curettage and disinfection of periodontal pockets. The Alexandrite laser has also shown highly promising results for selective calculus removal. Another promising characteristic is the ability of diode laser fluorescence to detect dental calculus.

The ultimate applicability and benefits of a novel treatment modality must be strictly evaluated based on scientific evidence and critical review of existing literature (3). Although the use of lasers for subgingival curettage and calculus removal in the treatment of periodontal pockets has been increasing among practitioners, the scientific studies indicating positive clinical results of lasers are still insufficient. Further basic and clinical studies, such as randomized controlled studies, are necessary to elucidate the actual effects and effectiveness of lasers in comparison with conventional treatment as well as negative side-effects.

To use lasers safely in a clinic, the practitioner should have precise knowledge of the characteristics and effects of each laser system and their applications as well as a full understanding of the conventional treatment procedures, and finally should exercise appropriate caution during their use.

A reliable procedure for laser application in nonsurgical periodontal therapy should be established by further studies, and clinicians should follow the results of scientific investigations to obtain successful outcomes. As understanding of the nature of laser light evolves, lasers will be used more effectively in the treatment of periodontal diseases. Laser systems applying the ablation effect of light energy, which is completely different from conventional mechanical debridement, may emerge as a new technical modality for nonsurgical periodontal therapy in the near future.

Acknowledgements

The authors wish to thank Dr Frank Schwarz, Heinrich Heine University, Dusseldorf, Germany; Dr Geena Koshy, Dr Koji Mizutani and Dr Aristeo Atsushi Takasaki, Tokyo Medical and Dental University, Tokyo, Japan; and Dr Yoshinori Ando, private practice, Tokyo, Japan for their kind advice and help in manuscript preparation. This review was supported by the grant for Center of Excellence Program for Frontier Research on Molecular Destruction and Reconstruction of Tooth and Bone in Tokyo Medical and Dental University.

References

Laser therapy in dentistry: a review of the literature from 1990 to 2000.

August 1997: 866–873.


35. Crespi R, Barone A, Covani U, Ciaglia RN, Romanos GE. Effects of CO2 laser treatment on fibroblast attachment to


