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In vitro evaluation of Er:YAG laser scaling of subgingival calculus in comparison with ultrasonic scaling

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The purpose of the present study was to evaluate the effectiveness of Er:YAG laser scaling and the morphological and histological changes of the laser-scaled root surface in comparison with the effectiveness and root surface changes produced by conventional ultrasonic scaling. Fifty-three periodontally involved human extracted teeth with a band of subgingival calculus were used. The teeth were divided randomly into 2 groups for laser scaling and ultrasonic scaling. Laser irradiation was performed at an energy output of 40 mJ/pulse and 10 pulses/s under water spray, with the probe tip contacted obliquely to the root surface. Ultrasonic scaling was performed at a clinically standard power setting. The time required for scaling, the scaled area and the temperature changes were determined using both methods of treatment. The features of the scaled surfaces were examined by histological and scanning electron microscope (s.e.m.) observations. The Er:YAG laser provided subgingival calculus removal on a level equivalent to that provided by the ultrasonic scaler, without major thermal elevation. Macroscopically, the laser-treated root surface was somewhat rougher than or similar to the ultrasonically scaled root. However, the efficiency of the laser scaling was lower than that of the ultrasonic scaling. In addition, histological examination revealed a thin deeply stained zone on the lased root surface, and s.e.m. analysis revealed a characteristic microroughness on the lased surface. The laser scaling provided a level of calculus removal that was similar to that provided by the ultrasonic scaling. However, the Er:YAG laser produced superficial, structural and thermal microchanges on the root cementum.

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Due to various advantageous characteristics, such as ablation or vaporization, hemostasis and the sterilization effect, laser treatment has been expected to serve as an alternative or adjunctive treatment to conventional, mechanical therapy in periodontics. CO_2 and Nd:YAG lasers, which are commonly used high power lasers, show an excellent soft tissue ablation capability, accompanied by an adequate hemostatic effect. As such, these lasers have been approved for soft tissue management in periodontics and oral surgery (1, 2). Since periodontium is composed of various tissues, including gingiva, periodontal ligaments, cementum and alveolar bone, both soft and hard tissues are always targeted in the use of lasers as a treatment for periodontal lesions. However, these lasers have not been shown to be effective for the treatment of hard tissues, such as the root surface or alveolar bone, due to the carbonization of these tissues and severe thermal side-effects on the target and surrounding tissues (3). Therefore, the use of these laser systems in periodontal therapy has been limited to soft tissue treatments, such as gingivectomy and frenectomy (4). Laser applications to hard tissues, such as the root surface or alveolar bone, have not been proved to be clinically promising.

Recently, the Er:YAG laser has been developed for use in dentistry, and the excellent ability of this laser to ablate hard tissues without producing major thermal side-effects has been demonstrated in various studies (5–8). The Er:YAG laser has been currently applied for caries treatment in the clinic, for which very promising results have been reported (9, 10). This laser has increased the number of possible laser applications in periodontics, as well as in restorative dentistry. Based on the promising characteristic of the Er:YAG laser oscillation wavelength (2.94 μm), which is highly absorbed in water and hydroxyapatite (5, 11), we have been investigating various possible applications of the Er:YAG laser for periodontal therapy, such as root surface debridement and soft tissue and bone tissue surgeries (12–15).

In the field of periodontics, preparation of the diseased root surface is one of the most promising procedures for Er:YAG laser application. Our previous *in vitro* studies have shown that the Er:YAG laser is effective for ablating subgingival calculus (12) and that this laser has sufficient bactericidal effects on periodontopathic bacteria at a low energy level (13). In addition, Yamaguchi *et al.* (16) and Sugi *et al.* (17) have suggested that Er:YAG laser irradiation might be useful in the elimination of lipopolysaccharides (LPS) on the diseased root surface. Thus, the Er:YAG laser is thought to have more promising properties for the treatment of periodontally diseased root surfaces than previous laser systems. However, the effectiveness of Er:YAG laser scaling, as well as its effect on the root surface, have not yet been evaluated thoroughly, compared to the conventional method.

Therefore, in the present study, we compared Er:YAG laser scaling and ultrasonic scaling, which is generally approved as a power-driven mechanical instrumentation, and evaluated both of these treatments with respect to the efficiency of scaling, morphological and histological changes of the scaled root surface, and thermal elevation during scaling. The laser scaling was performed under irradiation conditions, i.e. output power, irradiation method and type of contact tip used for irradiation, that are suitable to clinical application.

Materials and methods

Samples

Fifty-three periodontally involved human extracted teeth with a band of subgingival calculus were used for the *in vitro* experiments. The teeth were extracted for periodontal reasons and were obtained from patients who gave informed consent. The teeth were provided in part by a number of private dental offices and in part were collected from our department. The use of human teeth conformed to a protocol that satisfied the ethical standards of our institution. The extracted teeth were stored in water before use.

Laser apparatus

The laser apparatus employed in the present study was a pulsed Er:YAG laser (Model ML22, Erwin™; HOYA Continuum Corp., Tokyo, Japan, and J. Morita Mfg. Corp., Kyoto, Japan) (18). For this apparatus, the wavelength is 2.94 μm, the output energy settings range from 30 to 350 mJ/pulse, the pulse repetition rates (PRR) are 1, 3.3, 5 and 10 pulses/s (pps), and the pulse duration is 200 μs.

The laser apparatus employs a fiber delivery system that is integrated with a contact handpiece. The optical fiber is made of fluoride glass, and the contact tip is made of quartz glass fiber. In the present experiment, an 80-degree curved contact tip having a diameter of 600 μm and approximately 65% laser transmission was used (Fig. 1a). The apparatus also uses a special water spray system to cool the irradiated area. The contact tip is covered and protected by double metal tubes, which leaves spaces around the tip. From these spaces, air-mixed water is released coaxially to the contact tip, covering the target area during the irradiation. This water spray system provides precise and adequate water delivery.

Thermographic equipment

Medical infrared thermographic equipment (Thermo Tracer™ TH3107; NEC San-ci Instruments Ltd, Tokyo, Japan) was used for temperature measurement during scaling. This equipment is composed of a detector unit, a personal computer having an attached detector interface board, and a power isolation unit. The detector type is mercury–cadmium–tellunde (HgCdTe). The range of temperature measurement is $-10°C$ to $70°C$, and the temperature resolution is $0.1°C$. The accuracy of the measurement is $\pm 0.5\%$ range full scale.

Er:YAG laser scaling

Before the experiment, the operator received full training in calculus removal using the laser. The operator and assistants wore plastic-lens glasses for eye protection. The Er:YAG laser irradiation was performed under water spray (water: 17.0 ml/min, air: 3.3 l/min) at an energy output of 40 mJ/pulse and a PRR of 10 pps. The energy setting on the control panel was adjusted by measuring the output power at the tip of the contact probe using a power meter (Field master™, Coherent, USA). At an energy output of 40 mJ/pulse, the actual energy setting on the panel was greater than 60 mJ/pulse due to an approximate 35% energy loss in the contact probe. The energy output of 40 mJ/pulse was equivalent to the energy density of 14.2 J/cm^2/pulse at the tip of the contact probe. For the conditions of the water spray, air-mixed water at a flow rate that was sufficient to cover and cool the irradiated area was administered by adjusting the control dials, and the optimal amounts of air and water were thus determined.

Laser irradiation was performed in the contact mode, by maintaining the contact tip oblique to the root surface at an angle of approximately 30 degrees and moving the tip in a sweeping motion. The contact oblique irradiation was intended to minimize ablation of the tooth surface underlying the calculus, and thereby obtain a smooth root surface. Finally, the laser-treated root surface was finished using non-contact irradiation. The contact tip was replaced with a new tip after being used on 5 teeth due to a slight deterioration of the tip caused by the impact of calculus ablation during contact irradiation.

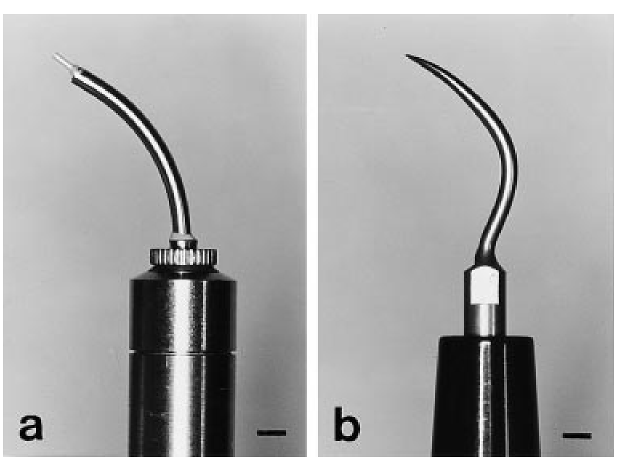

Fig. 1. Tips used for the scaling. (a) Er:YAG laser contact tip; 80-degree curved contact tip for Erwin™ apparatus, having a diameter of 600 μm and approximately 65% laser transmission. (b) Ultrasonic scaler tip; universal tip with a sharp point for Solfy™ apparatus. Original magnification: $\times 2$. Bar = 3 mm.

Ultrasonic scaling

An ultrasonic system (Solfy™, J. Morita Mfg Corp., Kyoto, Japan) and its universal tip with a sharp point (Fig. 1b) were used in this experiment. This device employs a piezoelectric type vibration system. Vibrations generated by an electronic transducer (ceramic vibrating element) inside the handpiece are transmitted to the tip of the instrument at a frequency of 27 ± 2 kHz. The vibration magnitude of the tip is 40–100 μm. The intensities of power and water can be adjusted in increments from 0 to 8 using a knob on the control box. The operation manual recommends a power setting of 2 to 6 for scaling. In the present experiment, a power setting of 4 and a water setting of 2 were selected, which are the standard conditions for clinical use of the device. The actual amount of sprayed water at this water setting was 33.0 ml/min. The ultrasonic scaling was conducted by contacting the probe obliquely to the root surface at an angle of approximately 15 degrees and moving the tip in a sweeping motion.

Experiment 1. Evaluation of efficiency of scaling and observation of features of the scaled site

Before dividing the teeth into two groups for laser scaling and ultrasonic scaling, 23 pairs of teeth (total: 46 teeth) having similar amounts of calculus deposition were selected from collected teeth. From each pair, one tooth was selected for laser scaling and the other was selected for ultrasonic scaling at random basis. Calculus removal was performed basically around the middle of the proximal surface, and the area of calculus removal was determined according to the condition of the calculus deposition of each sample. During scaling, each treatment was occasionally interrupted in order to inspect macroscopically the residual calculus on the scaled site. After confirming the completion of calculus removal macroscopically, each treatment was terminated. All teeth were inspected and photographed before and after treatment using a stereomicroscope (Model SZ6045TR, Olympus, Tokyo, Japan). During and after treatment, the following measurements and observations were conducted.

Determination of efficiency of scaling – The time required for removing calculus was determined for each treatment, not including the working time for the inspection of the residual calculus. The scaled area was traced onto tracing paper from photographs (magnification: $\times 8$) that were taken before and after scaling. The traced area was recorded into a personal computer using a scanner and was then calculated using software for measuring area

(NIH image, National Institutes of Health, USA). The efficiency of the scaling was expressed as the area scaled per second.

A Mann–Whitney *U*-test was applied as a statistical analysis in order to examine the significance of the difference in efficiency between the Er:YAG laser scaling and the ultrasonic scaling. Results were considered to be significant at $p < 0.05$. The analysis was conducted using StatView 4.11 software on a personal computer (Abacus Concepts Inc., Berkeley, USA).

Histological examination – After treatment, 4 teeth from each group were histologically examined. The teeth were fixed in phosphate-buffered 10% formalin, and were decalcified in formic acid–formalin solution. Specimens were then dehydrated in a series of graded ethyl alcohol solutions, embedded in paraffin, and serially cross-sectioned perpendicularly to the tooth axis at 4 μm thickness. Sections were stained with hematoxylin and eosin (H&E). The histological sections were examined under a light microscope (Leitz DMRX, Leica, Germany).

SEM examination – Eleven teeth from each group were subjected to scanning electron microscope (SEM) examination. Seven of the 11 teeth were used for the surface observation of the treated root. The teeth were immersed in phosphate-buffered 10% formalin for 4 days. Following fixation, the specimens were passed through a series of graded ethyl alcohol solutions at 30-min intervals. After immersion in isoamyl acetate for 30 min, the specimens were critical-point dried in liquid CO_2 using a critical point dryer (Model JCPD-5, JEOL Ltd, Tokyo, Japan). The specimens were then mounted and sputter-coated to have a gold coating 300 Å in thickness using an ion coater (Quick Auto Coater^{TM} SC-701 AT, Elionix Inc., Tokyo, Japan). The remaining 4 teeth of each group were cross-sectioned in the center of the scaled area, and were used for cross-sectional observation. The specimens were fixed in formalin and embedded in cold-curing epoxy resin (Epon 815, Nisshin EM Co., Tokyo, Japan). The cross-sectional surfaces were finished using wet silicone carbide papers up to #1500 and polished using diamond pastes having a particle size of down to 0.25 μm (DP-paste, Struers, Copenhagen, Denmark) and polishing cloths (DP-cloth; MOL and NAP, Struers, Copenhagen, Denmark). After desiccation at room temperature, the polished surfaces were sputter-coated with gold.

These prepared specimens were observed under SEMs (Model JXA-840 or T-20, JEOL Ltd, Tokyo, Japan) in order to examine the morphological features and microstructural changes of the treated root surface. A secondary electron image was obtained for each specimen at an accelerated voltage of 10–20 kV at various magnifications. The SEM picture of the surface analysis was photographed with a tilting angle of 50 degrees.

Experiment 2. Determination of thermal changes during scaling

Seven mandibular incisors with a band of subgingival calculus on the proximal surface were used. The mandibular incisors were chosen because these teeth, having the thinnest root in the dentition, would be most sensitive to heat generation during treatment. Six teeth out of the 7 were subjected to laser scaling and the remaining tooth was used for ultrasonic scaling as a control. In order to perform the temperature measurement for the pulpal side of the root, the proximal surface without calculus deposition was cut using a high-speed bur until half of the mesiodistal thickness of the root was removed, exposing the pulpal wall of each tooth. An opening having approximately the same shape as the tooth specimen was made in the middle of a plastic plate ($120 \times 120 \times 1.5$ mm), and the tooth specimen was fitted into the opening of the plastic plate. The small gap between the tooth and the plastic plate was then sealed with a soft wax so that the pulpal side of the tooth would not become wet due to the water that was sprayed on the root surface side during scaling.

The plastic plate with the tooth specimen was vertically fixed. A thermocamera was set in the direction perpendicular to the pulpal wall at the opposite side of the root surface that was to receive scaling. The laser scaling and the ultrasonic scaling were performed in the same way as that in experiment 1. The duration of laser irradiation or ultrasonic instrumentation was 60 s. Even when the calculus had been removed completely from the target area within a 60-s period, laser irradiation and ultrasonic instrumentation was continued in a sweeping motion for the entire allotted time. The temperature changes of the pulpal wall during scaling were recorded at 20-s intervals for 80 s from the beginning of scaling using the infrared thermographic equipment. After recording thermal images on the pulpal side of the root, temperature readings were made from the thermographic patterns on the monitor and the maximum temperature was recorded. After scaling, the thickness of each specimen was measured 3 times at the middle of the scaled site and these measurements were then averaged.

Results

Calculus ablation using the Er:YAG laser

The Er:YAG laser was found to be capable of ablating subgingival calculus effectively, by contacting the probe lightly to the root surface without placing pressure on the calculus. In the laser scaling, a much lower level of vibration was noted, compared to the ultrasonic scaling. Although a slight charring smell and popping sound were noted during calculus ablation using the laser, no major thermal damage such as carbonization was observed on the laser-treated root surface. Furthermore, the popping sound was masked by the noise of dental suction. Macroscopic inspection revealed that the scaling using the laser provided subgingival calculus removal on a level equivalent to that provided by the ultrasonic scaler. However, stereomicroscopic examination occasionally revealed very tiny residual calculi on the treated root surface of some specimens, including both laser-treated specimens and ultrasonically-treated specimens.

Macroscopically, the laser-scaled area had a whitish and somewhat rougher appearance compared to the ultrasonically scaled surface. Some laser-treated surfaces showed very similar smoothness to that of the ultrasonically-scaled surface (Fig. 2). The lased root surface became whitish when dried by air syringe, whereas the ultrasonically scaled root surface always took on a glossy appearance. Under stereomicroscopic observation, the lased root surface showed a slightly rugged or relatively flat appearance, and was occasionally accompanied by numerous white spots, whereas the root surface that was treated using the ultrasonic scaler generally showed a relatively smooth and glossy surface. However, several tracking grooves and small defects created by the ultrasonic tip instrumentation, as well as the ruggedness of the original root morphology, were often evident on the treated root surface.

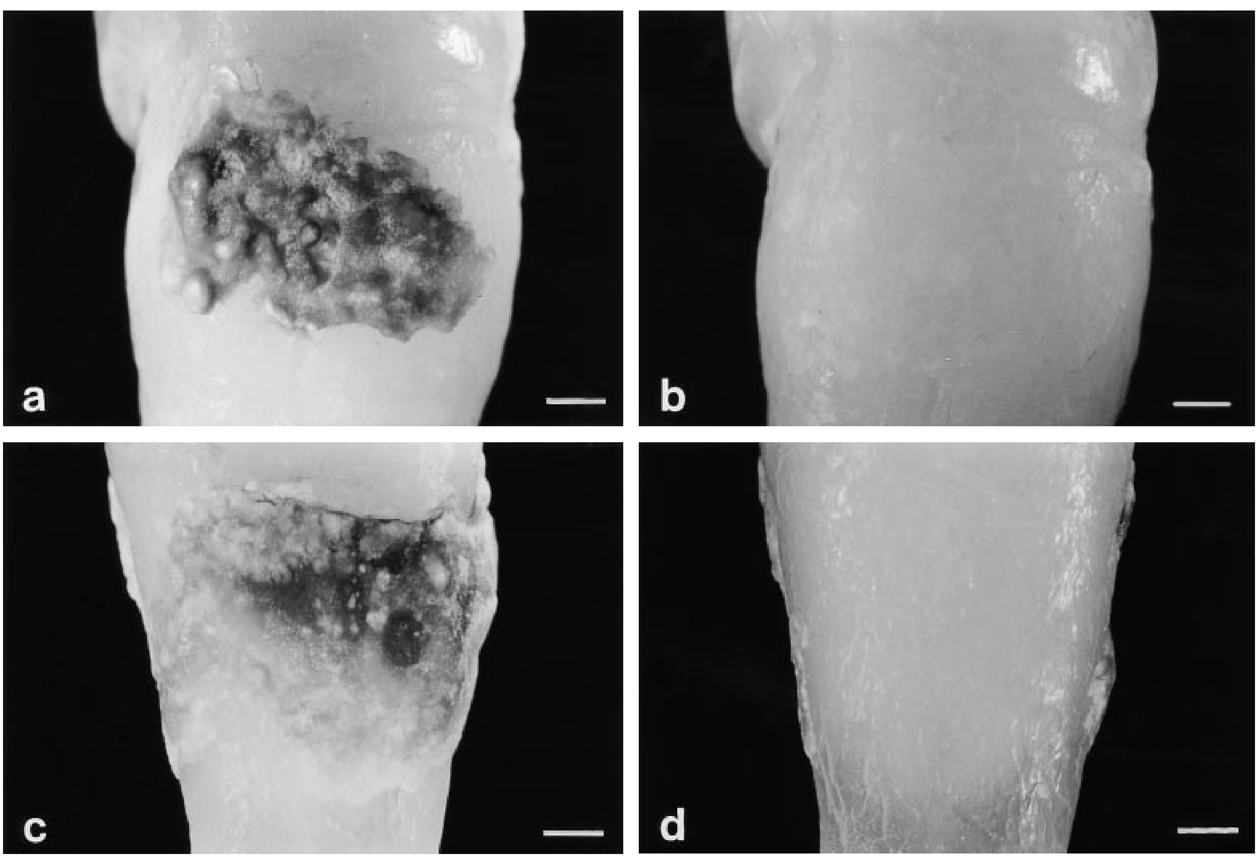

Fig. 2. Root surfaces before (a, c) and after (b, d) scaling of subgingival calculus. The Er:YAG laser scaling (a, b) was performed at 40 mJ/pulse and 10 pps under water spray. Laser irradiation was performed in the contact mode, maintaining the tip oblique to the root surface at an angle of approximately 30 degrees and moving the tip in a sweeping motion. Ultrasonic scaling was conducted under clinically standard conditions, contacting the probe obliquely to the root surface at an angle of approximately 15 degrees and moving the tip in a sweeping motion. Time of laser scaling (b) was 213 s, and that of ultrasonic scaling (d) was 122 s. Scaling using the laser provided subgingival calculus removal on a level equivalent to that provided by the ultrasonic scaler. The laser-scaled area shows a similar even appearance to that of the ultrasonically scaled surface. Original magnification: ×11.5. Bar = 1 mm.

Efficiency of scaling

Table 1 shows the efficiency of the scaling. The range of the efficiency was from 0.06 to 0.25 mm^2/s for laser scaling and from 0.08 to 0.42 mm^2/s for ultrasonic scaling. The average efficiency was 0.15 ± 0.05 mm^2/s (mean ± s.d., $n = 23$) for laser scaling and 0.20 ± 0.08 mm^2/s for ultrasonic scaling. Under the conditions of the present study, the laser scaling showed a lower efficiency than the ultrasonic scaling, as well as a significant difference ($p < 0.05$).

Although the ultrasonic scaler removed calculus more efficiently than the laser, the ultrasonic instrumentation tended to leave behind several tiny calculi more frequently in the treated area, compared to the laser scaling, and therefore often required additional operation time in order to completely remove the residual calculi under visual operation.

Histological observation

Histologically, no major thermal damage, such as cracking or carbonization, was observed for both treatments. The lased root surface generally showed some unevenness and micro-irregularity due to the ablation of the superficial part of cementum layer (Fig. 3a). The loss of tooth substance was generally observed within the layer of cementum and occasionally extended nearly to the dentin (Fig. 4a). The amount of cementum ablation was approximately 15–30 μm on average in the roots having approximately 60–140 μm of original cementum thickness. The maximum cementum loss was approximately 80 μm in the localized area showing exposure of dentin surface, as observed in 1 of the 4 specimens that was used for histological analysis. The remaining calculus that was intentionally left on the edge of the treated surface were tightly attached on the cementum.

The superficial layer of the lased cementum generally showed a minimal change with characteristic staining. The changed layer was composed of 2 layers: a surface layer stained deeply with hematoxylin (1–2 μm thickness) and a subsurface layer stained slightly to moderately with eosin (1.5–2.5 μm thickness) in the HE staining. The total width of the superficial zone having these stainings was approximately 2.5–4.5 μm (Fig. 5a). The deeply stained layer generally had a fragile

Table 1. Comparison of the efficiency of scaling between the Er:YAG laser and ultrasonic treatments

Er:YAG laser scaling				Ultrasonic scaling			
Sample no.	Scaled area (mm^2)	Time (s)	Efficiency (mm^2/s)	Sample no.	Scaled area (mm^2)	Time (s)	Efficiency (mm^2/s)
1	4.9	20	0.25	1	12.0	74	0.16
2	4.1	56	0.07	2	12.6	63	0.20
3	6.8	43	0.16	3	10.0	66	0.15
4	11.5	62	0.19	4	20.3	77	0.26
5	13.1	80	0.16	5	10.8	126	0.09
6	14.1	60	0.24	6	15.5	61	0.25
7	6.9	52	0.13	7	14.7	121	0.12
8	20.1	118	0.17	8	7.4	54	0.14
9	6.3	38	0.17	9	11.4	70	0.16
10	9.7	59	0.16	10	6.2	77	0.08
11	12.4	50	0.25	11	9.2	52	0.18
12	12.4	101	0.12	12	8.0	43	0.19
13	12.8	213	0.06	13	19.4	122	0.16
14	19.2	162	0.12	14	23.6	164	0.14
15	10.9	104	0.10	15	14.8	124	0.12
16	33.1	208	0.16	16	27.5	117	0.24
17	22.5	182	0.12	17	27.0	65	0.42
18	19.3	204	0.09	18	22.3	79	0.28
19	24.8	183	0.14	19	34.8	138	0.25
20	35.3	172	0.20	20	20.5	96	0.21
21	11.4	150	0.08	21	16.6	55	0.30
22	19.6	102	0.19	22	30.5	113	0.27
23	31.1	231	0.13	23	20.4	74	0.28
Mean ±SD			0.15 ±0.05				0.20 ±0.08
Statistic*			$p < 0.05$				

*Mann–Whitney *U*-test.

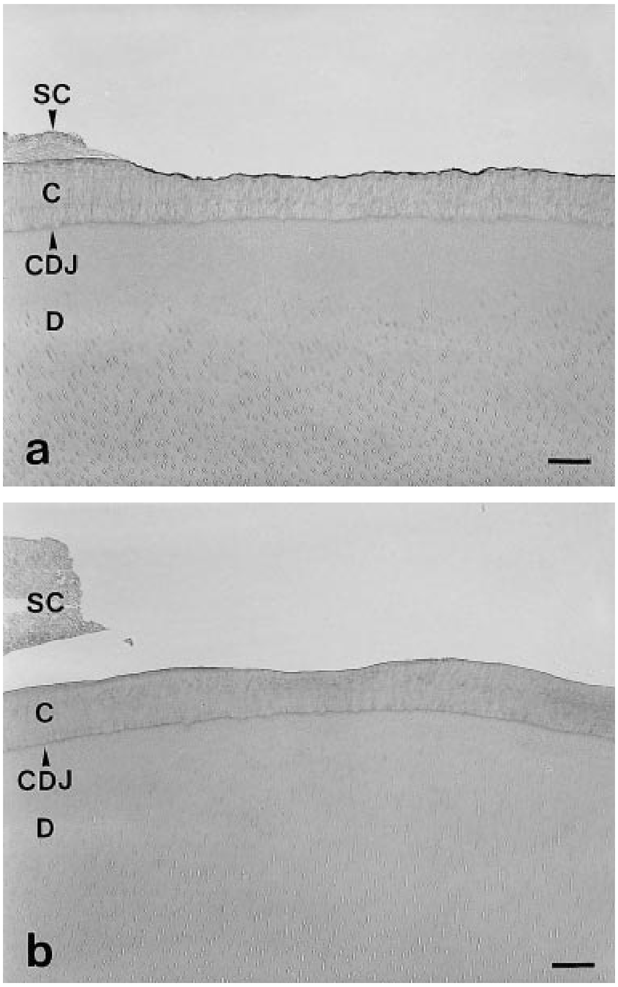

Fig. 3. Photomicrographs of a histological section of a scaled site. (a) Root surface scaled using the Er:YAG laser generally shows microirregularity due to the ablation of the superficial part of the cementum layer. A minimal change with deep staining is noted on the lased surface. (b) Ultrasonically scaled root surface shows a relatively even appearance and minimal cementum removal. "SC" indicates subgingival calculus that was intentionally left on the edge of the treated root surface, and the border of the scaled area is clearly indicated. C = cementum; CDJ = cemento–dentinal junction; D = dentin. Original magnification: ×160. Bar = 50 μm.

appearance, and a discontinuous pattern was occasionally observed.

In the ultrasonic scaling, the treated root showed a relatively even appearance with a smooth surface and without deep staining (Figs 3b, 5b). Loss of cementum was generally non-existent or minimal. However, localized concavities showing various degrees of cementum removal accompanied by superficial staining with hematoxylin and surrounding slight staining with eosin were occasionally observed on the treated root surface (Fig. 4b). The depth of concavity was generally 10–30 μm and the maximum depth of concavity reached approximately 80 μm.

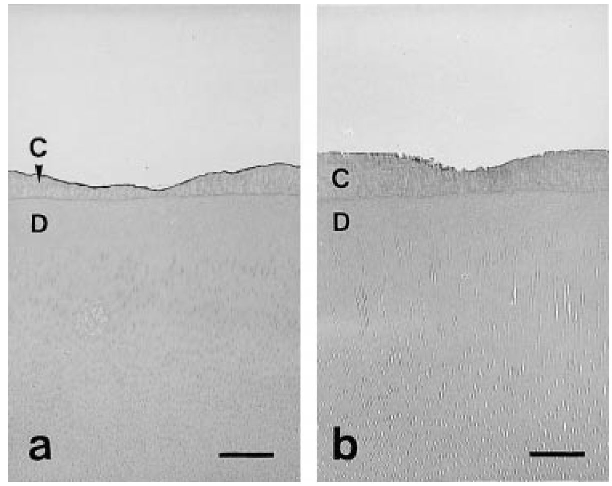

Fig. 4. Photomicrographs of an area having a large amount of cementum removal. Photograph (a) shows an area in the surface scaled using the Er:YAG laser, having a much greater amount of cementum ablation (approximately 60 μm in depth). Photograph (b) shows a localized cementum defect in the ultrasonically scaled surface, having a depth of 35 μm and superficial staining with hematoxylin, as well as a surrounding slight staining with eosin. C = cementum; CDJ = cemento–dentinal junction; D = dentin. Original magnification: ×116. Bar = 100 μm.

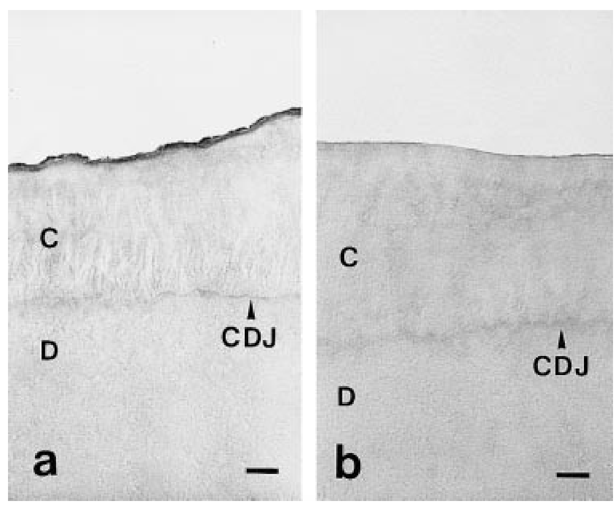

Fig. 5. Photomicrographs of the treated root cementum at high magnification. (a) Photograph is a typical Er:YAG lased cementum, showing a superficial deeply stained zone having a thickness of approximately 3–4 μm. The zone is composed of two layers: a surface thin layer stained deeply with hematoxylin, showing a fragile and discontinuous feature and a subsurface layer stained moderately with eosin in the HE staining. (b) The ultrasonically scaled root shows a smooth surface without deep staining. C = cementum; CDJ = cemento–dentinal junction; D = dentin. Original magnification: ×640. Bar = 10 μm.

SEM observation

SEM observation of the root surface that was treated by the Er:YAG laser had a relatively flat appearance at a low magnification. However, some shallow crater-like defects and linear tracking lines caused by the manipulation of the contact tip were occasionally observed on the lased root surface (Fig. 6a). The root treated using the ultrasonic scaler generally had a smooth surface, but shallow grooves and defects resulting from the ultrasonic tip instrumentation were occasionally observed (Fig. 6b). In one specimen that was subjected to ultrasonic scaling, wave-like features are evident on the treated surface, which was created by numerous deep grooves in the cementum, resulting in localized dentin exposures.

At high magnification, the SEM examination of the lased root surface revealed a characteristic microroughness. Numerous round or sharp pointed projections resulting from the cementum ablation were evident on the lased root surface (Fig. 7a, b). Occasionally, openings of dentinal tubules were observed, indicating the exposure of underlying dentin. The ultrasonically scaled surface generally had a smooth appearance covered with a smear layer (Fig. 7c). However, micro-irregular structures were sometimes observed in the area of the deep defects and grooves at high magnification (Fig. 7d). The ablated surface of the remaining calculus that was intentionally left on the root showed flaky appearance without melting features. Microparticles were observed on both of the original (non-lased) and lased surfaces of the calculus. (Fig. 8).

In the cross-sectional observation, the laser-treated root surface showed superficial micro-irregularity and degradation, in contrast to the smoothness of the root surface that was treated

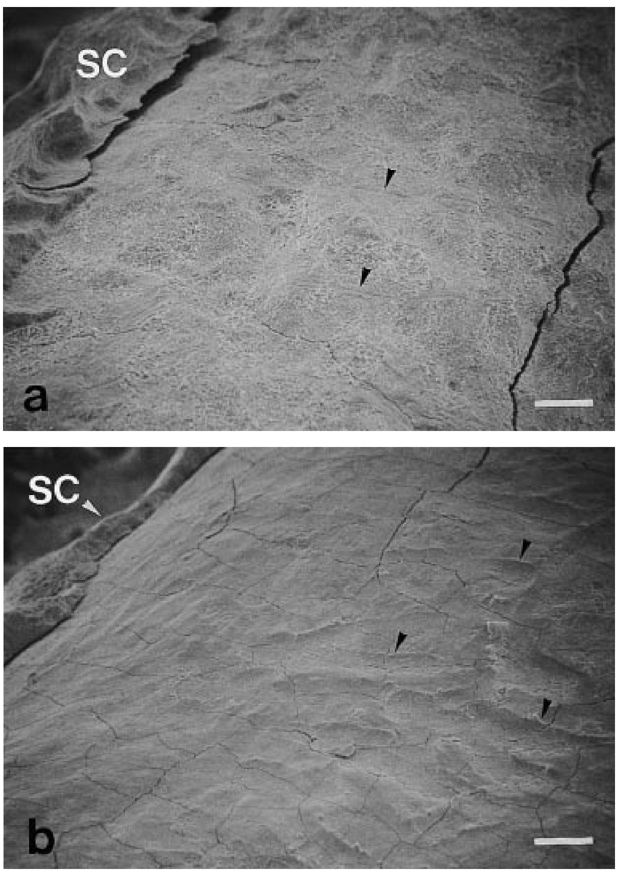

Fig. 6. Scanning electron micrographs of the scaled root surface. (a) Root surface scaled using the Er:YAG laser has a somewhat rugged appearance. Some shallow crater-like defects and linear tracking lines (arrows) caused by the manipulation of the contact tip are partially evident on the lased root surface. (b) The ultrasonically scaled surface is smooth, but has shallow grooves and defects (arrows) resulting from the ultrasonic tip instrumentation. "SC" indicates subgingival calculus that was intentionally left on the edge of the treated root surface. Visible cracks in the cementum in both photographs and partial separation of the calculus from the root surface in photograph (a) are the result of the shrinkage artifacts. Original magnification: $\times 35$. Bar $= 300$ μm.

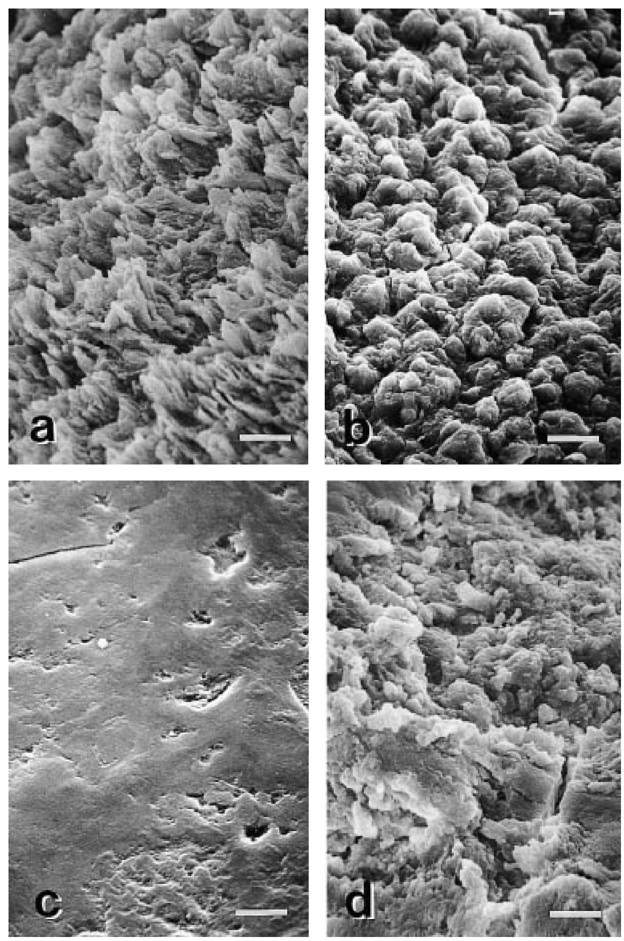

Fig. 7. Scanning electron micrographs of the scaled surface at high magnification. The Er:YAG lased root surface (a, b) reveals a characteristic microroughness that contrasts the smooth ultrasonically scaled root surface (c). Numerous sharp pointed (a) or rounded projections (b) are evident on the lased root surface. Although the ultrasonically scaled surface generally shows a smooth appearance covered with a smear layer (c), the area of deep defects and grooves revealed microirregular structures (d). Original magnification: $\times 1000$. Bar $= 10$ μm.

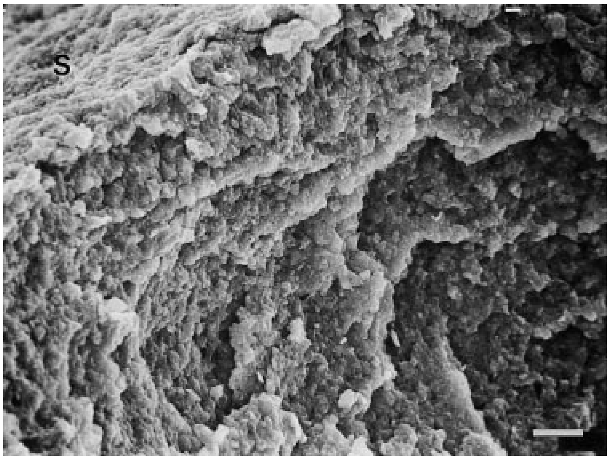

Fig. 8. Scanning electron micrograph of the ablated surface of the subgingival calculus at high magnification. The calculus was intentionally left on the edge of the treated root. The Er:YAG lased surface shows flaky appearance without melting features. "S" shows an original, non-lased surface of calculus. Microparticles are observed on both of the original and lased surfaces. Original magnification: ×1000. Bar = 10 μm.

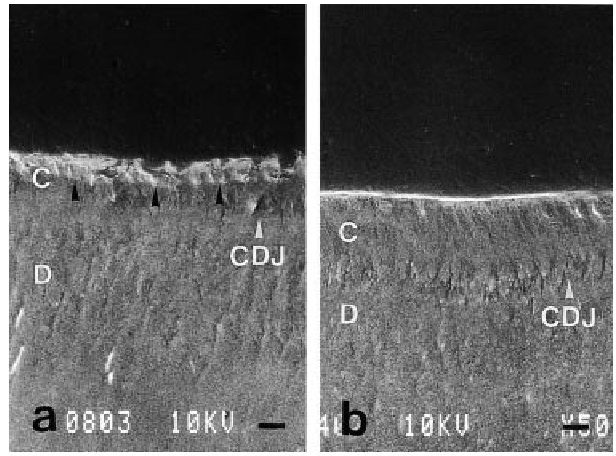

Fig. 9. Scanning electron micrographs of the cross-section of the scaled root surface. The photographs show a secondary electron image of the polished surface of the cross-section of the specimen embedded in epoxy resin. (a) Photograph is a typical Er:YAG lased root surface, showing a superficial micro-irregularity and microstructural degradation that contrasts the smooth root surface (b) that was treated using the ultrasonic scaler. Here, the change in width of the changed layer of lased cementum is approximately 7 μm. Black arrows indicate the border of the changed zone. Original magnification: ×500. Bar = 10 μm.

using the ultrasonic scaler. The width of the damaged layer of the lased cementum was 5–10 μm (Fig. 9).

Thermal change

Figure 10 shows the results of the temperature measurement at the pulpal side during scaling. In the laser scaling, the temperature rose gradually according to the progress of scaling procedure, reached the maximum level at around 40 s after the beginning of scaling and returned to the original temperature at around 20 s after the end of scaling. In some specimens of the laser scaling, the final temperature showed a lower level than the temperature before treatment. The maximum thermal elevation of the pulpal wall during laser scaling with water spray ranged from 0.6 to 2.2°C (0.6, 1.0, 1.2, 1.7, 1.9, 2.2) and the average thermal elevation was 1.4 ± 0.6°C (mean ± s.d., $n = 6$). The water spray effectively minimized heat generation. In the ultrasonic scaling, the temperature change in the pulpal wall during ultrasonic scaling was minimal and the thermal elevation was only 0.1°C. The mean thickness of the six specimens that received laser scaling was 1.30 ± 0.13 mm (mean ± s.d., $n = 6$) at the scaled site, and the thickness of the specimen for ultrasonic scaling was 1.40 mm.

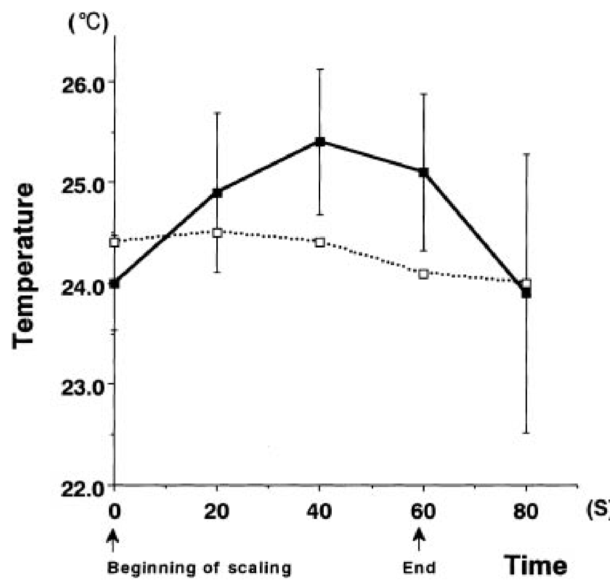

Fig. 10. Temperature changes during the Er:YAG laser scaling (LS) and the ultrasonic scaling (US), respectively. Scaling was performed on the proximal surface of the mandibular incisors using a band of subgingival calculus. The data show the results of the temperature measurement at 20-s intervals at the pulpal side during scaling. Data for the laser scaling represents the mean ± s.d. of 5 independent experiments. -■-, LS; ···□···, US.

Discussion

Application of the Nd:YAG and CO_2 lasers to the periodontally diseased root surface has been investigated previously, and advantageous properties of the Nd:YAG laser, such as removal of a smear layer on the root surface produced by conventional mechanical debridement (19) and inactivation of endotoxin in exposed cementum (20), have been demonstrated. In 1997, the US

Food and Drug Administration approved sulcular debridement or soft tissue curettage by means of the Nd:YAG laser, and the laser pocket curettage in adjunct to the conventional mechanical root surface treatment has gradually come to be performed by general practitioners (21). However, for root surface debridement, the Nd:YAG laser is not capable of ablating calculus effectively and causes significant thermal damage, such as melting and cracking on the root surface when a high energy output is applied (22, 23). The CO_2 laser easily carbonizes hard tissues such as root and bone surfaces (24, 25). Thus, due to insufficient calculus elimination ability and side effects of distinct root surface alteration induced by heat generation during irradiation, Nd:YAG and CO_2 lasers can not achieve root surface debridement to a satisfactory degree.

Recently, hard tissue treatment using the Er:YAG laser has been shown to be effective and efficient (5–10). Our previous preliminary report showed that the Er:YAG laser used in combination with water irrigation was capable of removing subgingival calculus from the root effectively without causing major thermal damage (12). The results suggested the possibility of Er:YAG laser application to debridement of periodontally diseased root surfaces. Following the *in vitro* study, Watanabe *et al.* conducted a clinical trial of the laser scaling and confirmed the safety and effectiveness of the procedure clinically (14).

In the present study, we investigated and clarified the effects of Er:YAG laser scaling using clinical irradiation conditions in comparison with those of ultrasonic scaling. The energy output and other parameters were determined based on the results of our previous studies (12, 14). In our preliminary experiment, which employed perpendicular contact irradiation to the root surface, an energy level of 30 mJ/pulse was considered to be suitable for the calculus ablation at the PRR (pulse repetition rate) of 10 pps (12). In the oblique irradiation of the present experiment, a slightly higher output energy of 40 mJ/pulse was chosen in order to compensate for the decrease in the energy density due to the widening of the irradiation spot size. The 10 pps was selected as the highest PRR for the employed laser apparatus. As a result, Er:YAG laser scaling was found to enable the same degree of subgingival calculus removal as the ultrasonic scaling. The treated surface became much more even compared to the cases treated by perpendicular contact irradiation in our previous experiment (12). By performing careful manipulation of the contact handpiece in a sweeping motion using the oblique contact irradiation mode, loss of tooth substance was minimized and thereby reduction of the irregularity of the lased root surface was achieved. Although a mild to moderate irregularity was still evident in some cases of laser scaling, a number of irregularities were also partly observed in the ultrasonic scaling. Previous studies have shown that ultrasonic scalers produce defects of various depth and volume, depending on the combination of various working parameters (26). In the present experiment, the cause of the irregularity in both treatments is attributed to existence of the softened cementum, hard calculus attachment to the root surface and original irregular morphology of the root surface.

The laser scaling induced some temperature elevation (0.6–2.2°C) in the pulpal wall of the proximal surface of mandibular incisors. A temperature rise of within 5°C in the pulp has been reported to be safe for pulp survival (27). Therefore, this level of temperature rise on the pulpal wall during laser scaling is considered to be within the physiologically tolerable levels to the pulp tissues.

Histological and SEM examination showed that the Er:YAG laser ablated not only the calculus, but also the superficial to deep portion of the underlying cementum, and that the treated surface had characteristic microstructures resulting from cementum ablation. These findings indicate that the Er:YAG laser did not have sufficient selective calculus ablation ability at the irradiation conditions used in the present study. In the debridement of the diseased root surface, not only the removal of calculus, but also removal of the contaminated cementum are required. Therefore, a certain amount of cementum ablation during calculus removal using the Er:YAG laser may be clinically acceptable. However, recent studies suggest that pathological changes exist only in the superficial layer of the periodontally diseased surface, and therefore the deeper layer of cementum should be preserved (28, 29). Under the present irradiation conditions, selective calculus elimination using the Er:YAG laser was still difficult and technically dependent. Therefore, careful irradiation performance using the optimal output energy setting was required in order to prevent excessive cementum ablation. Regarding the selective calculus removal, Rechmann *et al.* recently reported the excellent characteristics of the frequency-doubled Alexandrite laser (30). The Alexandrite laser seems to have a promising characteristic for selective calculus removal.

With regard to the alteration of the root surface, the Er:YAG lased root surface histologically showed minimal changes with a characteristically stained zone. The changed zone was composed of two layers, superficial deeply stained layer with hematoxylin and subsurface layer stained with eosin. These layers may be due to microstructural degradation and thermal denaturation of the cementum. The difference of the staining condition may be associated with the degree of degradation of the cementum. Especially, the superficial deeply stained layer with hematoxylin seemed to have fragile structures and was occasionally observed to be discontinuous in the histological sections. Also, the changed layer in the histological section showed a thinner width (2.5–4.5 μm) compared to the width (5–10 μm) observed via the cross-sectional s.e.m. The discontinuity of the superficial deeply stained layer as well as the difference in thickness of the changed layer between histological and s.e.m. examinations may be attributed to the possibility that the fragile microstructure of the superficial layer of the lased cementum was partially or totally lost during the decalcification process of the histological sample preparation. Therefore, it is speculated that the superficial deeply stained layer may be highly damaged, exhibiting both microstructural degradation and thermal denaturation, whereas the underlying subsurface layer may be affected by some thermal denaturation.

Thus, Er:YAG laser irradiation produces a characteristic microstructural change as well as minimal thermal influence on the treated root surface. Fujii *et al.* reported similar micromorphological changes on the root surface following single-pulse, contact Er:YAG laser irradiation at 75 mJ/pulse and showed a 15-μm layer of damaged tissue on the Er:YAG-lased cementum (31). Based on these findings, the Er:YAG-lased root surface may give some influence to cell attachment. Therefore, the attachment of the periodontal tissue to the lased root surface must be evaluated in further studies. In addition, the necessity and usefulness of additional treatment to remove the superficially changed layer of the lased root surface using acid treatment or root planing via hand instruments should be investigated. On the other hand, as shown in previous studies, the Er:YAG laser has the potential beneficial property of sterilizing bacteria (13) and eliminating LPS (16, 17), and thereby disinfection and detoxication may be highly expected on the laser-treated root surface. Furthermore, the laser provides calculus elimination with extremely low mechanical stress and may be capable of reaching sites that conventional, mechanical instrumentation cannot reach. These low stress and potentially high accessibility are also advantageous properties of laser treatment.

Under the conditions of the present study, Er:YAG laser scaling showed a somewhat lower efficiency than the ultrasonic scaling. However, the efficiency would be easily improved by the use of a higher output power, or the use of a PRR higher than 10 pps that would be enabled by the development of new laser device. Considering the safety and effective irradiation parameters for clinical use, the combination of higher PRR and lower energy output is recommended in order to increase the efficiency of calculus ablation and simultaneously decrease the amount of cementum loss. For such irradiation conditions, the efficiency is improved without increasing the uncomfortable vibration stress experienced by the patients and, at the same time, selective calculus removal using the Er:YAG laser may be more feasible. Although the efficiency of ultrasonic scaling can be increased by using a higher power setting, the increase in uncomfortable vibrations and thermal and mechanical damage to the root is inevitable due to the elevation of operation power.

At present, the use of the Er:YAG laser as a scaling instrument is limited to visual operation, for subgingival calculus removal on the exposed root surface with gingival recession, and the ablation of the contaminated root surface and remaining calculus during flap surgery. However, the Er:YAG laser has various potential applications in periodontal surgery, because the Er:YAG laser has an excellent ablative effect for both of soft and hard tissues (14). Recontouring of bone tissue (15), removal of diseased soft tissue within a narrow and deep, vertical bone defect and disinfection of the operation field, as well as root surface preparation, during flap surgery may be highly possible for the Er:YAG laser. Further basic and clinical studies are required in order to clarify the potential application of the Er:YAG laser in periodontal therapy.

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