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Original Paper

Effect of Pulse Duration of Er: YAG Laser on Dentin Ablation

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The present study examined the effects on dentin ablation efficiency arising from various pulse durations of Er: YAG laser at a fixed energy fluence. Ten flat human dentin disks were prepared and exposed to an Er: YAG laser at 1 pps for three seconds at pulse durations of 100 — 500 μsec with 150 mJ/pulse (40.0 J/cm^2•pulse). The depth and diameter of the ablated dentin were measured and the ablation volume was estimated. Irradiated surfaces and cross-sections were observed using a SEM. Depth of the removed dentin increased and the diameter of the spot decreased without a change in the estimated volume at increased pulse durations. SEM observation of the irradiated surfaces revealed that there were no morphological differences when the pulse duration was changed. When the specimens were cross-sectioned, the ablated dentin had a dome shape and there was a dark layer under the irradiated surface.

Key words: Er: YAG laser, Pulse duration, Dentin ablation

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INTRODUCTION

Since the introduction of ruby laser to human teeth[1)], many experiments have reported on the effects of different laser systems — such as ruby, CO_2, and Nd: YAG lasers — on dental hard tissues[2-4)]. The results of early experiments with lasers were not promising because of insufficient ablation efficiency and undesirable side effects such as melting, cracking and charring of enamel and dentin, and pulpal damage caused by overheating[3-7)]. However, subsequent advances in laser research have resulted in clinically useful wavelengths, an ability to set the physical and technical parameters, and a provision for water cooling[8-11)].

The wavelength of Er: YAG laser is endowed with the highest absorption in water and has a high affinity for hydroxyapatite[12)]. The laser energy couples into the hydroxyl radical in the apatite crystal and the water that is bound to the crystalline structures of the tooth[12)]. Vaporization of water within the mineral substrate causes a massive volume expansion, and this expansion causes the surrounding material to be exploded away[12)]. In light of this phenomenon, the Er: YAG laser system is the most promising laser device for caries treatment[13-16)] and a more comfortable alternative or adjunctive method to conventional mechanical cavity preparation[17)]. Nowadays, Er: YAG laser has been used clinically for caries removal and cavity preparations.

The Er: YAG laser system is a device of pulse oscillation mode. Pulse shape is a function of pulse duration, intensity, and repetition rate. Pulse duration is one essential physical parameter of laser light that determines its interaction with matter[18)]. The pulse duration of most Er: YAG lasers on the market is fixed from 150 to 250 μsec, and the majority of published experiments have been performed with fixed pulse durations in that range[13-17,19)]. Few researchers have examined the influence of varied pulse durations on dentin ablation with Er: YAG laser[20,21)]. Ebihara *et al.*[20)] evaluated the depth of irradiated cavities of root canal dentin and reported that shorter pulse durations featured a deeper ablation effect at about 20 J/cm^2. This was much lower than the fluence usually employed for cavity preparations with Er: YAG laser in the dental clinic. Similarly, Majaron *et al.*[21)] examined the influence of energy density with several pulse durations on the efficiency of dentin ablation. Different effects for different pulse durations were observed at different energy fluences. It is also noteworthy that although the investigation[21)] was carried out using a wide range of energy fluences, precise evaluation with an appropriate energy fluence for dentin ablation was not performed. Indeed, the present study was the first attempt that investigated the effect of pulse duration in detail with a suitable energy fluence for dentin ablation.

To date, some *in vivo*/*in vitro* articles have reported on the output energy which was suitable for dentin preparation with varying diameter tips[16,17,19]. Dostalova *et al.*[16] indicated that the optimal energy for dentin preparation was 200 mJ/pulse with a spot size of 0.30−0.35 mm, while Keller *et al.*[17] selected between 150 and 300 mJ/pulse with a 0.7-mm diameter tip for dentin ablation. Shigetani *et al.*[19] evaluated the volume of ablated dentin cavities by Er: YAG laser irradiation with various energy fluences and concluded that the appropriate laser energy was 100 mJ/pulse using a 0.4-mm or 0.6-mm diameter tip. The appropriate energy fluence for dentin ablation reported in these three experiments was within the range of 24.1−59.7 J/cm^2, considering an energy loss of 25−30% in the probe.

The purpose of this study, therefore, was to evaluate the effect of pulse duration of Er: YAG laser on the efficiency of dentin ablation. To this end, a special Er: YAG laser device was constructed whereby experiments were carried out using pulse durations varying from 100 to 500 μs, while energy fluence remained constant at a level recommended for dentin treatment.

MATERIALS AND METHODS

Sample preparation

Ten extracted intact human molars stored in deionized water with 0.01% (w/v) thymol were used for this study. After removing the roots, the teeth were sectioned longitudinally to obtain dentin disks of about 1 mm in thickness using a low-speed saw (Isomet, Buehler, IL, USA) with water coolant. The surface of each disk was polished with silicon carbide papers and diamond pastes (DP-Paste P, Struers, Copenhagen, Denmark) down to 0.25 μm.

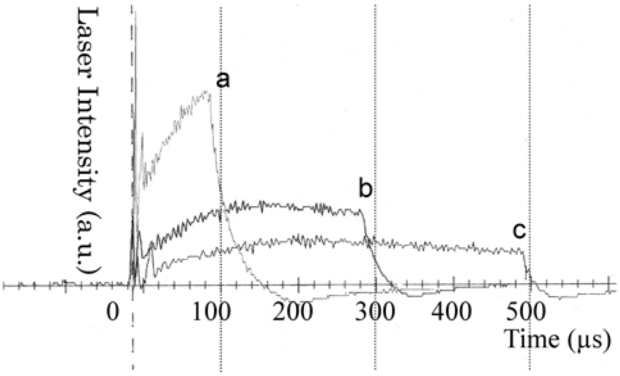

Fig. 1 Time-based pulse profiles at 150 mJ/pulse: (a) 100 μs, (b) 300 μs, (c) 500 μs.

Laser apparatus

A specially constructed Er: YAG laser device (HOYA Photonics, Tokyo, Japan) was used in this study. Wavelength was 2.94 μm, output energy setting ranged from 30 to 350 mJ/pulse, pulse repetition rate ranged from 1 to 60 pulses per second (pps), and pulse duration varied from 100 to 500 μsec. Laser beam was delivered to the handpiece *via* a fiber made of fluoride glass. Laser output was through a straight contact probe made of quartz glass with a diameter of 600 μm connected to the handpiece. A water spray system was employed for cooling the irradiated area.

Laser irradiation

Each dentin disk was fixed to a glass slide with wax and a cyanoacrylate gel (Model repair II blue, Dentsply-Sankin, Tochigi, Japan). The handpiece was fixed vertically to the experimental surface of the dentin disk by a clamp. After adjusting the distance to 120 μm between the tip of the probe and the surface of the dentin disk, laser was applied. Pulse durations employed in this study were 100, 150, 200, 300, 400, and 500 μsec, while energy setting was fixed at 150 mJ/pulse. At an energy setting of 150 mJ/pulse, the actual energy at the tip of the probe was approximately 113 mJ/pulse. This was due to an approximate 25% energy loss in the probe and an energy density of about 40.0 J/cm^2 per one pulse. At a fixed energy level, the maximum value of laser intensity decreased as the pulse duration increased (Fig. 1).

In this study, a repetition rate of 1 pps for three seconds with a water spray (water: 17.6 ml/min; air: 1.2l ml/min) was chosen. From a preliminary study, the time of laser irradiation was thus determined by measuring the depth of the irradiated spots. The number of specimens in each group was 10. Each sample was irradiated at six different pulse durations in different areas.

Laser microscope analysis

After irradiation, the depth and diameter of each irradiated spot were measured by a laser surface profile micrometer (VF-7510, Keyence, Osaka, Japan). Volume of ablated dentin was considered as half of an oval ball and was calculated as follows:

$$V = \frac{4}{3}\pi \times r^2 \times \frac{d}{2} \times \frac{1}{2} = \pi r^2 \times \frac{d}{3}$$

where r is the radius of ablated surface of dentin and d is the depth of ablated dentin.

Data were analyzed by one-way analysis of variance (ANOVA) and Tukey's HSD test at a 95% level of confidence.

SEM morphology

After measurement with a laser surface profile micrometer, the irradiated surfaces of the specimens were observed and cut into cross-sections. To observe the irradiated surface, the teeth were dried in a desiccator and sputter-coated with gold. For the cross-sections, the samples were embedded in an epoxy resin (Epon 812, TAAB, London, UK) and a cross-cut surface was prepared using a glass knife set on a microtome (Reichert Ultracut S, Reichert-Leica, Vienna, Austria). The cross-cut samples were dried and sputter-coated as for the surface observation. Using a scanning electron microscope (SEM; JSM-5310LV, JEOL, Tokyo, Japan), the irradiated surfaces and cross-cut sections were examined for morphological changes.

RESULTS

Depth of cavity after laser irradiation

Figure 2 shows the depths of the cavities after laser irradiation with various pulse durations. The spots became deeper with increasing pulse duration. The average cavity depths following laser irradiation of 100, 150, 200, 300, 400, and 500 μs pulse durations were 0.23±0.02, 0.23±0.01, 0.25±0.02, 0.26±0.02, 0.27±0.02, and 0.28±0.02 mm respectively. One-way ANOVA showed that pulse duration affected the depth of irradiated cavity ($p<0.05$). Tukey's HSD test revealed that there were significant differences between 100 μs and 300 μs, 400 μs, 500 μs, between 150 μs and 400 μs, 500 μs, and between 200 μs and 500 μs ($p<0.05$).

Diameter of cavity after laser irradiation

Figure 3 shows the diameters of the cavities after laser irradiation. The longer the pulse duration of Er: YAG laser, the smaller the diameter of the irradiated spot. The average cavity diameters following laser irradiation of 100, 150, 200, 300, 400, and 500 μs pulse durations were 0.67±0.01, 0.67±0.02, 0.66±0.01, 0.65±0.02, 0.64±0.02, and 0.63±0.02 mm respectively. One-way ANOVA showed that pulse duration affected the diameter of irradiated cavity ($p<0.05$). Tukey's HSD test revealed that there were significant differences between 100 μs and 400 μs, 500 μs, between 150 μs and 400 μs, 500 μs, and between 200 μs and 500 μs ($p<0.05$).

Volume of cavity after laser irradiation

Figure 4 shows the volumes of the cavities after laser irradiation. The average cavity volumes following

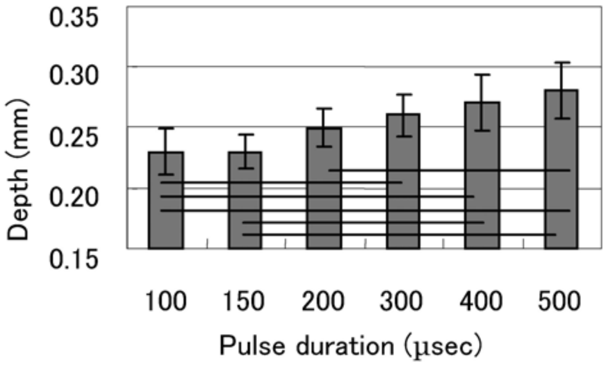

Fig. 2 Depths of ablated dentin after laser irradiation. As the pulse duration of Er: YAG laser increased, depth of the cavities increased. Bar indicates significant difference ($p<0.05$).

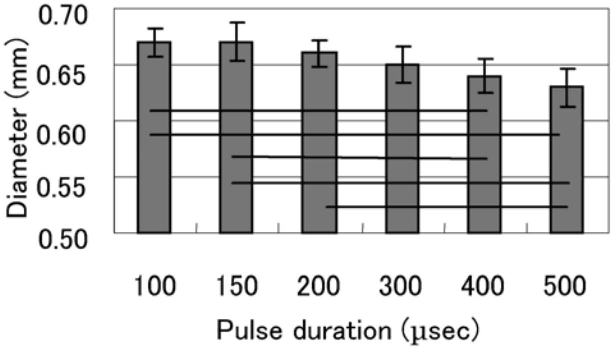

Fig. 3 Diameters of ablated dentin after laser irradiation. As the pulse duration of Er: YAG laser increased, diameter of the cavities decreased. Bar indicates significant difference ($p<0.05$).

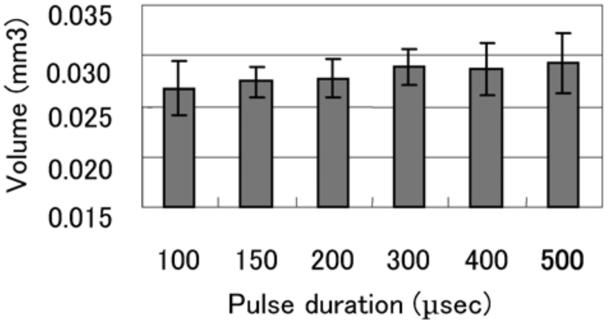

Fig. 4 Estimated volumes of ablated dentin after laser irradiation. Volume of the cavities did not change statistically with the pulse duration of Er: YAG laser. There were no significant differences ($p>0.05$).

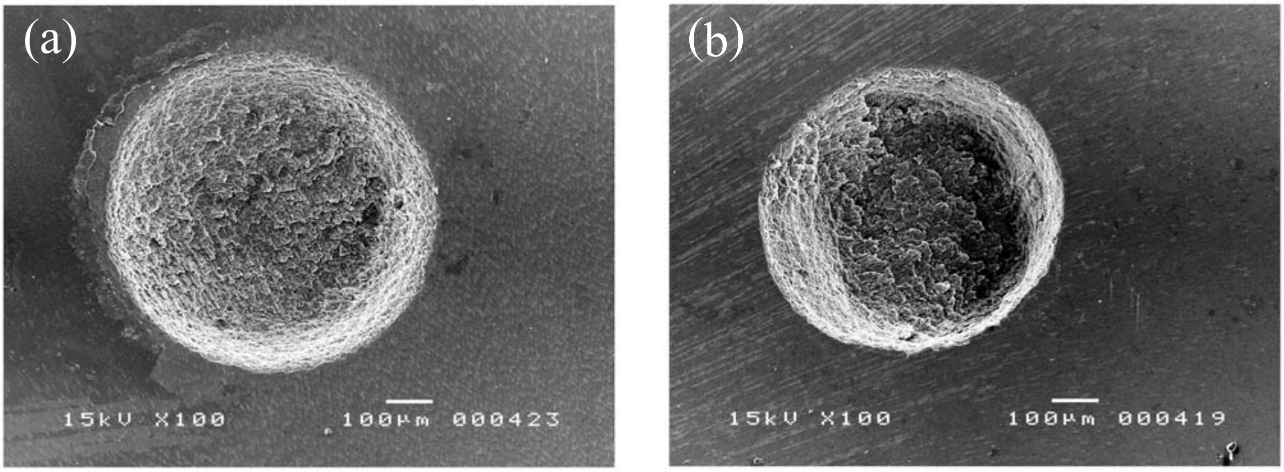

Fig. 5 Scanning electron micrographs showing typical morphological changes of laser-irradiated surfaces at 100 µs (a) or 500 µs (b) at low magnification. The lased surface showed a scaly and flaky structure. Original magnification ×100; bar=100 µm.

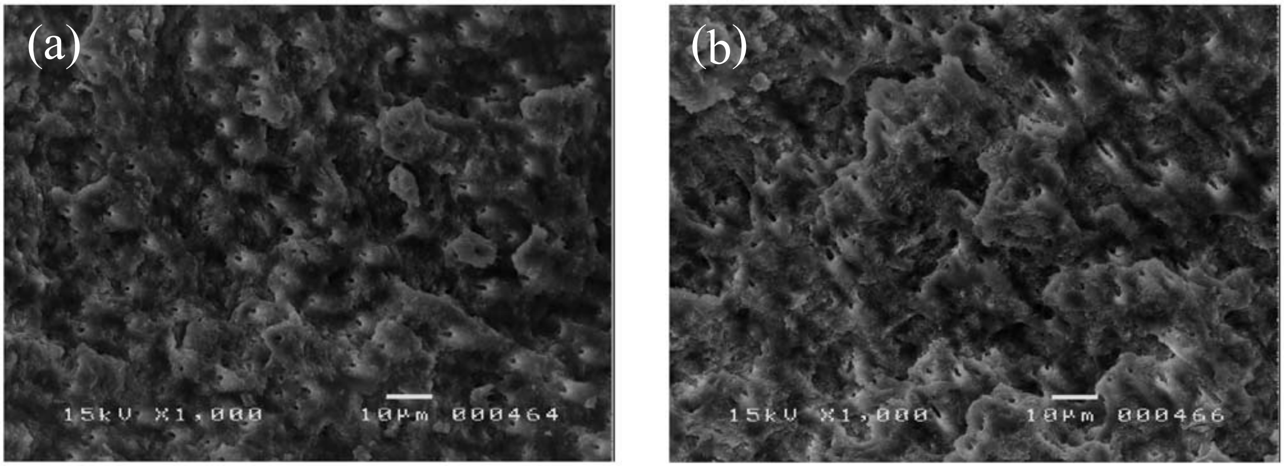

Fig. 6 Scanning electron micrographs showing typical morphological changes of laser-irradiated surfaces at 100 µs (a) or 500 µs (b) at high magnification. The lased dentin surfaces lacked a smear layer and had open dentinal tubules, and no evidence of melting and recrystallization. Original magnification ×1000; bar=10 µm.

laser irradiation of 100, 150, 200, 300, 400, and 500 µs pulse durations were 0.027±0.003, 0.027±0.002, 0.028±0.002, 0.029±0.002, 0.029±0.003, and 0.029±0.003 mm^3 respectively. One-way ANOVA revealed that the volume of laser ablation was not influenced by pulse duration ($p>0.05$).

SEM observation

Figures 5 and 6 are representative SEM images of the typical morphological changes after laser irradiation. There were no morphological differences among the experimental groups. At low magnification, the lased spot surface showed a scaly or flaky structure (Fig. 5). At a higher magnification, it was revealed that the lased surface lacked a smear layer and had open dentinal tubules. There was also no evidence of melting and recrystallization (Fig. 6). Figure 7 shows the SEM image of the cross-sectioned specimen. For each condition, the craters were dome-shaped. SEM observation of the cross-sections revealed that there was a dark layer of approximately 10 µm thickness under the irradiated surface.

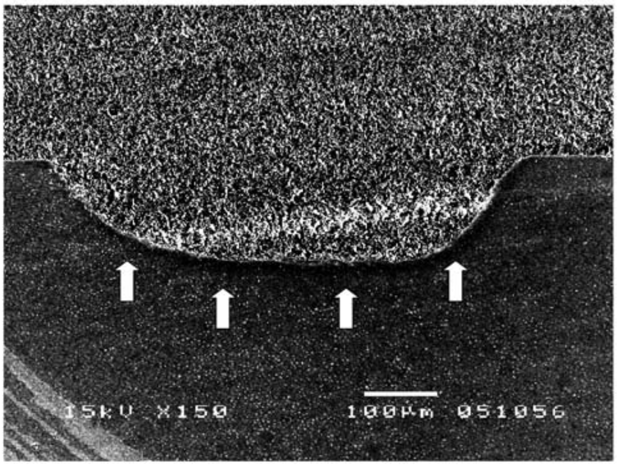

Fig. 7 Scanning electron micrographs of a cross-sectioned specimen at 100 μs. Craters have a regular dome shape. There was also a dark layer of approximately 10 μm thickness (arrows) under the irradiated surface. Original magnification ×150; bar=100 μm.

DISCUSSION

With a view to evaluating the effects of pulse duration on dentin ablation efficiency, we used a specially constructed Er: YAG laser device of which the pulse duration could be varied from 100 to 500 μs, while the output energy remained constant. The pulse durations used in this study were 100, 200, 300, 400, and 500 μsec, as well as a pulse duration of 150 μsec which was employed in a marketed dental laser device.

To date, few researchers have examined the effects arising from varied pulse durations of Er: YAG laser[20-23]. With varied laser pulse durations and energy fluences of Er: YAG laser, Majaron *et al.*[21] quantitatively examined their effects on depth and diameter and calculated the crater volumes thereof. The authors chiefly focused on energy density and did not discuss pulse duration in detail. At about 40 J/cm^2, they found that the spots of ablated dentin became deeper as pulse duration increased from 50 to 300 μs — results similar to ours in the present study. The diameter of irradiated spots did not manifestly change under these conditions. The reason for the different results could be caused by the thermal effect arising from 10 consecutive laser pulse irradiations without water spray cooling. Ebihara *et al.*[20] reported that an Er: YAG laser with 80-μs pulse duration featured a deeper ablation effect than 180 and 280 μs at 20 J/cm^2. The main purpose of their study[20] was to determine the surface and subsurface modifications of root canal dentin after Er: YAG laser irradiation under variable conditions. In their study[20], energy densities in the range of 12−37 J/cm^2 were employed, which were lower than that recommended for efficient dentin ablation. It should be highlighted that a lower energy fluence might have a different impact on the results.

In the field of laser beam machining, results similar to our experiment for the depth and diameter of ablated spots were obtained using a microslab MOPA laser on silicon and iron (unpublished data). Although the irradiation conditions and ablation mechanism were different from dentin ablation, they were the only comparable data which we could find. As the pulse duration increased at a fixed energy level, the maximum value of laser intensity became smaller (Fig. 1). The maximum value of laser intensity and pulse duration might affect the changes in depth and diameter of the ablated dentin.

In this study, the laser was applied at 1 pps for three seconds to measure the depth of the spot by a laser surface profile micrometer. Before laser irradiation, the distance between the tip of laser probe and dentin disk surface was adjusted to 120 μm. In this study, whenever one pulse was irradiated, the distance between the tip and dentin surface was increased. It should be highlighted that the distance between the tip and the irradiated surface is one factor which controls the interaction of the laser and the irradiated tissue. In other words, results might have been influenced as the distance between the tip and irradiated surface gradually increased with increase in the number of laser pulses. Therefore, with precise control of this distance, the effect of pulse duration on the depth of ablated dentin might be manifested more expressly.

In the present study, the lased spot became deeper, but the diameter of the spot became smaller, as pulse duration increased. The estimated volumes of ablated dentin were not statistically different between pulse durations. With a fixed energy fluence, a longer pulse duration could achieve deeper ablation with a smaller surface area. Therefore, in terms of clinical application, long pulse durations should be recommended for more precise control of an ablation area.

SEM analysis indicated no debris on the cavity walls after irradiation. There was no evidence of thermal damages such as surface cracking or carbonization in any of the experimental groups. With the cross-sectioned samples, there was a dark layer of about 10 μm thickness under the irradiated surface in all the experimental groups. Previous investigations on bone ablation with Er: YAG laser have found that the thermal-affected zone was 5−15 μm from the surrounding tissues[9,24]. As for Sasaki *et al.*[25], their report revealed only minimal changes without severe thermal damages — such as microstructural changes of the original apatite and reduction of the organic matrix — on a bone surface treated with Er: YAG laser. Aoki *et al.*[15)] suggested that the dark zone under the irradiated surface of root dentin using Er: YAG laser might be due to thermal and microstructural degeneration. As for the dark layer observed in this study, it was thought to be the thermal-affected layer.

By means of SEM, Camerlingo *et al.*[22)] observed the dentin surfaces which were irradiated by Er: YAG laser with pulse durations from 100 to 1000 μs, and also analyzed the lased surface in each condition with micro-Raman spectroscopy (μ-RS). At 100 μs pulse duration, the SEM images were similar to those of the present study. Using μ-RS analysis, it was shown that there was no evidence of the formation of β-tricalcium phosphate compounds that were generated from hydroxyapatite when it was heated at high temperature[26)]. From both analyses, the authors suggested that the dentin surface lased with a pulse duration of 100 μs was clearer with the absence of a smear layer and debris, and indicated stronger modification of the organic components than that lased with a pulse duration of 1000 μs. In the present study, we observed no morphological differences and no changes in the thickness of the dark layer with pulse durations of 100−500 μs. However, this does not preclude the possibility of differences with a wider pulse duration range. Therefore, more detailed analyses are needed in order to clarify the effects of pulse duration on lased dentin.

In the present study, increasing the pulse duration resulted in increased depth of ablated dentin but decreased diameter, without morphological differences. In the cross-sectioned specimens, a dark layer was observed under the irradiated surface with all pulse durations. Leveraging on the results of this study, further studies are recommended and urged with a view to establishing a reliable procedure for Er: YAG laser ablation in the dental clinic. These studies would include examining the influence of pulse duration in caries removal, in the adhesion characteristic of lased dentin to adhesive restorative materials, and in imparting antibacterial properties to irradiated surfaces.

CONCLUSION

As the pulse duration increased, the ablated dentin became deeper but the diameter thereof decreased. SEM observation of the irradiated surface revealed that changes in pulse duration were not accompanied with morphological differences. In the cross-sectioned specimens, a dark layer was observed under the irradiated surface with all the pulse durations.

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