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ORIGINAL ARTICLE

Effects of the percentage of air/water in spray on the efficiency of tooth ablation with erbium, chromium: yttrium-scandium-gallium-garnet (Er,Cr:YSGG) laser irradiation

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Abstract
We aimed at examining the effects of a percentage of air/water in spray on the cutting efficiency of Er,Cr:YSGG laser for enamel and dentin. The intensity and frequency of irradiation were 3.0 W and 20 Hz for the enamel surface and 2.0 W and 20 Hz for the dentin surface, respectively. Flattened surfaces of enamel and dentin were irradiated at nine points for approximately 1 s under various percentages of air/water in spray using Er,Cr:YSGG laser. A high-speed video microscope was used to record each laser irradiation on the tooth surface. A slow video image was used to count the number of water micro-explosions yielded on the tooth surface during laser irradiation. A surface roughness tester was used to measure the depth of the dimple prepared with laser irradiation on each specimen. Each individual depth of dimple was divided by the number of water micro-explosions (pulse). This allowed for the calculation of the cutting depth per pulse. Following laser irradiation, several representative specimens were observed using an SEM. Two-way ANOVA was used as the statistical analysis. This revealed that there was no significant effect of the percentage of air/water in spray on the cutting depth for enamel surface ($p > 0.05$). On the contrary, a significant effect was observed in air-ratio for dentin cutting ($p < 0.05$). Both enamel and dentin were characterized by the presence of rough surfaces, as shown by the SEM images of the dimples. The percentage of air/water in spray was not significantly effective in laser cutting for enamel. Air-percentage was significantly effective in laser cutting for dentin.

Keywords Erbium, chromium: yttrium-scandium-gallium-garnet (Er,Cr:YSGG) laser · Tooth cutting · Enamel · Dentin · High-speed camera

Introduction

Several past studies have evaluated the laser tooth cutting [1–10]. It has been shown that Er:YAG, Er:YSGG, and Er,Cr:YSGG lasers all possess a high efficacy of tooth ablation with respect to other lasers. Furthermore, Er,Cr:YSGG laser has shown an excellent cavity preparation time, resembling the rotary cutting instruments with air-turbine handpiece [2, 6]. Compared with the rotary tooth-cutting method, the other benefits of cavity preparation with Er,Cr:YSGG laser included reduction in the thermal damage for the tooth tissues, no smear layer on the prepared tooth surface, and less vibration caused to the micro-crack formation [2, 6].

The tooth-cutting mechanism by means of a mid-infrared laser differs from that using a rotary cutting device. Mid-infrared laser wavelengths, such as Er,Cr:YSGG (2780 nm) or Er:YAG (2940 nm), are well absorbed into water. The water absorption coefficients of Er,Cr:YSGG and Er:YAG are 1200 mm^{-1} and 400 mm^{-1}, respectively [11]. The Er:YAG laser penetrates approximately 7 μm in enamel and 5 μm in dentine [11]. The Er,Cr:YSGG laser penetrates three times deeper than the Er:YAG laser does. Therefore, the earlier theory for the mechanism of action of laser tooth ablation describes the absorption of the laser beam by the aqueous components in the tooth substrate, followed by a blast of tooth structure due to evaporation of the water. However, this earlier theory appears to be not probable. This is due to the fact that approximately one half of the water in tooth substrates is diffusible. Furthermore, the water diffusion is very slow (i.e.,

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taking several hours to days) and temperatures of up to 800 °C would be required to remove water from the tooth structure [12–14]. The wavelength of the CO_2 laser group (far-infrared) is also absorbed into water and hydroxyapatite. The enamel absorption coefficients and depths of 9300 nm, 9600 nm, 10,300 nm, and 10,600 nm CO_2 laser were 5500 cm^{-1} and 2 μm, 8000 cm^{-1} and 1 μm, 1125 cm^{-1} and 9 μm, and 825 cm^{-1} and 12 μm, respectively [15]. Therefore, the wavelengths 9300 nm or 9600 nm were more suitable for enamel ablation than other wavelengths. Not only the function of hydroxyapatite's absorption but also its reflection and transmittance have to be considered when determining the wavelength at which the peak energy is transmitted into the enamel. When considering both the reflection and absorption, the total energy transferred into hydroxyapatite was maximum at 9300 nm, where the reflection coefficient was low but the absorption coefficient was fairly high [16]. Thus, the maximum energy transfer may realize the rapid ablation and vaporization of tooth substances.

Past studies demonstrated that tooth ablation with Er,Cr:YSGG laser irradiation is produced by a transpiration of hydration shell in hydroxyapatite due to the high absorption levels of the laser energy into the water [2, 6]. Furthermore, some studies discuss the hydrokinetic theory in which the water droplets energized by the photons of a laser break the hydroxyapatite. This had been previously proposed as the mechanism of tooth ablation with Er,Cr:YSGG laser [3, 4]. Mir M et al. analyzed the laser ablation images obtained by a high-tech camera and found that the external water micro-droplets were plunged into the inter-prism of enamel during irradiation. Furthermore, they observed that the thermal effect of laser on injected micro-droplets led to the explosion of tooth tissue [6]. However, Kuščer L et al. reported an opposite opinion for the hydrokinetic theory [7]. More specifically, they measured Er:YAG and Er,Cr:YSGG laser-ablated volumes in dental hard tissues under a broad range of tested laser parameters and water-cooling conditions. Their goal was to verify whether the hydrokinetic effect could be a possible alternative to the subsurface water expansion for hard-tissue laser ablation. Following their study, the authors observed no evidence of the hydrokinetic effect [7].

A more recent study has proposed a mechanism of tooth ablation for erbium laser. Specifically, the authors suggest that the rapid subsurface expansion of laser-heated water trapped within the interstitial structure of tooth tissues causes a massive volume expansion. As a consequence, this expansion leads the surrounding tissues to explode [17]. Moreover, they observed that the spray during laser irradiation cleans the irradiated tooth surface, and the ablation rate efficiency increases by means of the ablation process [18]. Therefore, the externally supplied water has a significant influence on leading to an effective laser tooth ablation process when the Er,Cr:YSGG laser is used.

We previously reported on the mechanism of laser tooth ablation by monitoring with high-speed camera. Specifically, we observed that at the moment of laser irradiation, micro water explosions occurred on the tooth surface [19]. The speed of the laser cutting could be affected by numerous laser irradiation parameters such as intensity, frequency, water-ratio, and air-ratio in spray. However, the effect of these parameters on cutting character has not been sufficiently clarified. Therefore, with the present study, we aimed at examining the effects of the percentage of air/water in spray on the cutting efficiency of Er,Cr:YSGG laser for both enamel and dentin. Our null hypothesis was that the percentage of air/water in spray would not influence the tooth-cutting efficiency of Er,Cr:YSGG laser.

Materials and methods

The Human Research Committee of the Nippon Dental University School of Life Dentistry at Niigata reviewed and approved the present study (approval number ECNG-H-9).

Specimen preparation

Extracted human anterior teeth preserved in 0.01% thymol solution at 4 °C were used in this study. The teeth were sectioned at the cement–enamel junction to remove the roots; next, the crowns were trimmed perpendicularly and horizontally to the tooth axis to prepare sections (approximately 5 × 5 × 3 mm) using an Isomet (Buehler Ltd., Lake Bluff, IL, USA). The labial surfaces of the sections were ground flat to the enamel or dentin using 600-grit silicon carbide paper (Carbimet, Buehler, Lake Bluff, IL, USA) and finished with 1500-grit paper using a polishing machine (Lewel specimen polisher, Kasai, Yokohama, Japan) under water irrigation. These were then used as specimens ($n = 10$).

Tooth cutting and monitoring

The specimen surfaces were irradiated at nine points for approximately 1 s under various percentages of air/water in spray using Er,Cr:YSGG laser (Waterlase MD, Biolase Technology, San Clemente, CA, USA) (Tables 1 and 2). The MX5 sapphire tip with turbo handpiece was positioned perpendicular to the specimen surface using a flexible arm for a uniform focal irradiation distance of 3 mm. Irradiation with focus mode was subsequently performed. Intensity and frequency of irradiation shown in the touchscreen display were 3.0 W and 20 Hz for the enamel surface, and 2.0 W and 20 Hz for the dentin surface, respectively. A high-speed video microscope (VW-5000, Keyence, Osaka, Japan) was used to record each laser irradiation on the tooth surface. The slow video image was used to determine the number of water

Table 1 Experimental groups for enamel cutting

Group	Air-ratio (%)	Water-ratio (%)	Water flow rate (mL/min)
70A-60W-E	70	60	15.0
70A-70W-E	70	70	17.0
70A-80W-E	70	80	18.6
80A-60W-E	80	60	15.8
80A-70W-E	80	70	16.4
80A-80W-E	80	80	17.5
90A-60W-E	90	60	14.6
90A-70W-E	90	70	15.4
90A-80W-E	90	80	16.7

micro-explosions yielded on the tooth surface during laser irradiation.

We verified the actual power output using a power meter (Nova II Display Rohs, Ophir Optronics, Jerusalem, Israel). The actual power outputs for 3 W and 2 W displayed on the touchscreen were 2.2 W and 1.47 W, respectively. As the diameter of the laser beam with a focus was 0.5 mm, the area of laser irradiation was 0.196 mm^2 or 0.00196 cm^2. Therefore, the power densities for 3 W and 2 W displayed on the touchscreen were 1122.5 W/cm^2 (2.2 W/0.00196 cm^2) and 750.0 W/cm^2 (1.47 W/0.00196 cm^2), respectively. The energy densities for 3 W and 2 W displayed on the touchscreen were approximately 1122.5 j/cm^2 and 750.0 j/cm^2, respectively, because the laser irradiation time was approximately 1 s. We also measured the actual water flow rates (in mL/min) for each experimental group (Tables 1 and 2).

Measurement of cutting depth on the tooth surface per pulse

A surface roughness tester (Surfcom 470A, Tokyo Seimitsu, Japan) was used to measure the depth of dimple prepared with laser irradiation on each specimen. In order to calculate the cutting depth per pulse, the depth (i.e., cutting depth) was divided by the number of water micro-explosion (pulse).

Table 2 Experimental groups for dentin cutting

Group	Air-ratio (%)	Water-ratio (%)	Water flow rate (mL/min)
50A-60W-D	50	60	8.6
50A-70W-D	50	70	17.4
50A-80W-D	50	80	18.8
60A-60W-D	60	60	12.6
60A-70W-D	60	70	18.2
60A-80W-D	60	80	19.4
70A-60W-D	70	60	15.0
70A-70W-D	70	70	17.0
70A-80W-D	70	80	18.6

SEM observation

Following the laser irradiation, representative specimens were selected from each group for further evaluation of the cut surfaces using an SEM (S-800, Hitachi, Chiyoda, Tokyo, Japan). The selected specimens were sputter-coated with palladium and platinum and subsequently observed using an acceleration voltage of 15 kV.

Statistical analysis

Statistical analysis was performed using the two-way ANOVA. The goal was to examine the effect of the percentage of air/water in spray on the efficacy of laser cutting (Microsoft Excel 2010 for Windows, SSRI Co. Ltd., Tokyo, Japan).

Results

The cutting depths (mean ± SD) of both the enamel and dentin surfaces are reported in Tables 3 and 4, respectively. Two-way ANOVA was used to perform statistical analysis. The latter revealed that there were no significant effects of both the percentage of water and air on the laser cutting depth for enamel surface ($p > 0.05$). On the contrary, we observed a significant effect of air-ratio factor on the cutting depth for dentin surface ($p = 0.01$). A statistically significant interaction between the two factors was not detected. We performed Tukey's HSD test for the analysis of the air-ratio factor. This test revealed that the cutting depth of the 50% air application group was significantly deeper than that of the 70% air application group ($p = 0.008$).

Figure 1 shows the representative stereomicroscope image of dimples on the dentin specimen. These were prepared by laser irradiation under various air/water ratios in spray. The representative SEM images of the dimples prepared on both enamel and dentin surfaces are shown in Figs. 2 and 3, respectively. All of the dimples exhibited a conical shape, and their surfaces were remarkably rough. Numerous very small cracks and debris from melted tooth were observed on the surface of both enamel and dentin dimples.

Discussion

We initially performed a pilot study, in which the mechanism of laser ablation with an Er,Cr:YSGG laser was confirmed, with the aid of a high-speed video microscope. In order to obtain a clear video image of laser ablation for enamel, in the pilot study, the conditions of laser irradiation were set to

Table 3 Mean and SD of enamel cutting depth for one laser pulse

Group	Cutting depth (mean ± SD, μm)
70A-60W-E	10.38 ± 2.66
70A-70W-E	10.51 ± 3.33
70A-80W-E	9.77 ± 2.59
80A-60W-E	9.24 ± 2.46
80A-70W-E	9.68 ± 1.19
80A-80W-E	8.50 ± 1.22
90A-60W-E	9.64 ± 2.79
90A-70W-E	10.22 ± 3.54
90A-80W-E	9.90 ± 3.49

be 4 W, 20 Hz, 60% air, and 40% water. During the laser ablation, light was irradiated to the enamel surface with spray. At this time, a video image was recorded at the enamel surface for a few seconds using the high-speed video microscope (× 50 magnifications). Following the analysis of the recorded video image (flame rate 250), we observed a flash explosion of the water at the enamel surface, where the laser light of one pulse was irradiated. We speculated this phenomenon as a water micro-explosion. When the water micro-explosion took place, the enamel surface was excavated and led to the formation of a crater-like tiny dimple. The results of this pilot study indicated that the tooth surface was excavated and led to formation of a crater-like tiny dimple when the water micro-explosion occurred on the laser-irradiated tooth surface. These findings supported “rapid subsurface expansion of laser-heated water” as the theory of laser tooth ablation (suggested by Van As G) [17].

In the present study, the high-speed video microscope was used to analyze the water micro-explosions during laser cutting. The analysis was performed both qualitatively and quantitatively using the playback slow video image. To calculate the cutting depth per pulse, the depth of a dimple was divided by the number of water micro-explosions. This calculation allowed us to obtain a comparison between tooth-cutting ability for each laser irradiation and various percentages of air/water in spray.

Table 4 Mean and SD of dentin-cutting depth for one laser pulse

Group	Cutting depth (mean ± SD, μm)
50A-60W-D	9.84 ± 2.17
50A-70W-D	9.47 ± 1.53
50A-80W-D	9.42 ± 1.61
60A-60W-D	9.29 ± 2.11
60A-70W-D	8.58 ± 1.49
60A-80W-D	8.40 ± 1.90
70A-60W-D	8.03 ± 1.23
70A-70W-D	8.10 ± 1.67
70A-80W-D	8.47 ± 1.63

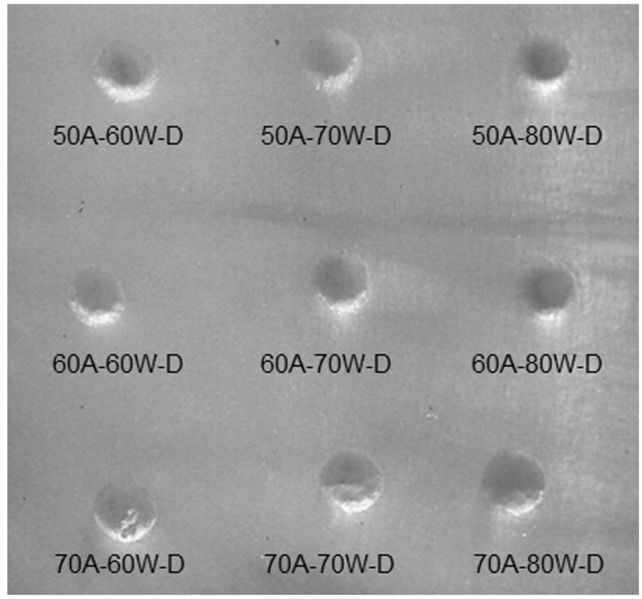

Fig. 1 Stereomicroscopic image of dimples prepared with the laser irradiation accompanied by each percentage of air/water in spray on the dentin surface

When analyzing the results for enamel laser cutting, we observed that neither the percentage of water nor the percentage of air in the spray significantly influenced the efficiency of laser cutting. In clinic, when using Waterlase MD 60% air in spray is generally recommended for cutting tooth substrate. However, in the present study, the percentages of air/water in spray for enamel cutting were 60, 70, and 80% and 70, 80, and 90%, respectively. These settings were selected to analyze in a definitive manner the effects of air rates on the cutting efficacy. Of note, in previous studies 85% air in spray was used to investigate the morphological changes and bond strength of resin composite in prepared cavities with Er,Cr:YSGG laser [19, 20]. We hypothesized that the above-mentioned percentages of air/water in spray for enamel cutting were too high to define statistical significances among the experimental groups. On the contrary, the condition of 70% water was the deepest among all the percentages for air group. The percentage of water may be more significant for laser cutting efficacy than the percentage of air. Mir et al. examined the influence of water-laser interaction on the enamel surface during irradiation with an Er:YAG laser. Furthermore, the authors evaluated the effects of different distances between the laser tip and the enamel surface. They concluded that the volume of cuts per pulse depended significantly on the variability of the water thickness, and showed a tendency to decrease with the thickening of the water layer [5]. In the present study, a high percentage of air lead to a fairly thinner water layer on the enamel surface. As a result, the percentage of water

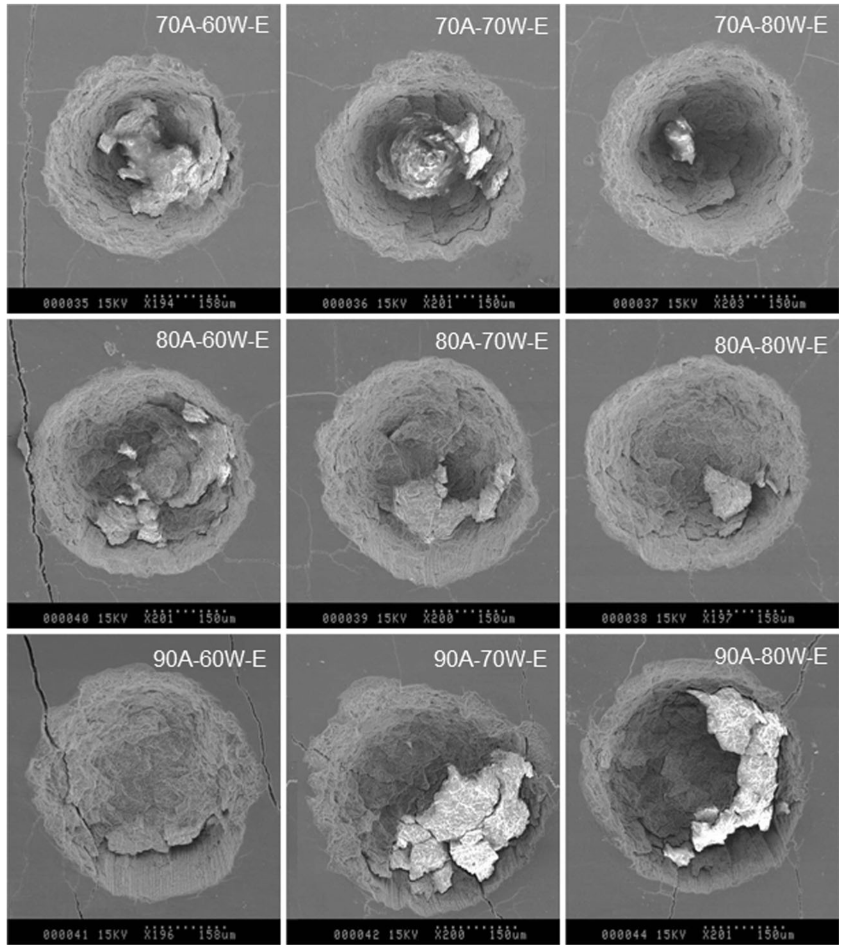

Fig. 2 SEM images of enamel dimples prepared with the laser irradiation accompanied by each percentage of air/water in spray

under a high percentage of air might not influence the efficacy of laser cutting.

With the laser dentin cutting, we observed that the percentage of air in spray significantly influenced cutting efficiency. Deeper dimples were observed in the 50% the percentage of air group compared to the 60% and 70% air-ratio groups. We conclude that a lower the percentage of air has a better dentin-cutting efficacy than higher the percentage of air, when the percentage of air is between 50 and 70%. In the past, it has been speculated that the strength of water microexplosions with a higher percentage of air might decrease compared to lower the percentage of air, since high air pressure might disturb water molecules laying on the dentin surface. Colucci et al. reported that dental tissues Er:YAG laser ablation with different water flow rates influenced the amount of mass loss. The authors concluded that the water flow of Er:YAG laser affected the ablation rate [21, 22]. Although the wavelength of the Er,Cr:YSGG laser (2780 nm) was slightly different from that of the Er:YAG laser (2940 nm), both wavelengths were well absorbed in water. Accordingly, the dentin-cutting efficacy of the Er,Cr:YSGG laser may be influenced by water flow rates in the same manner as that of the Er:YAG laser.

SEM pictures, represented in Figs. 2 and 3, showed considerably rough surfaces on laser-irradiated enamel and dentin outer layers. The roughness of Er,Cr:YSGG laser-ablated enamel and dentin surfaces have been reported in several previous studies [19, 20, 23, 24]. The percentage of air/water in spray during laser cutting might not influence the texture of the laser-cut surface. By observing the configuration of the conical dimples, we conclude that the high-energy pulse laser beams with spray repetitively excavated the central area of a laser-irradiated tooth surface. Judging from the profile recorded with the surface roughness tester and the SEM observation for the laser-ablated tooth surface, all tooth surface dimples prepared with laser irradiation exhibited a conical shape. The characteristic conical shape of the dimple might be due to a Gaussian distribution of the output power of the laser used in this study. When comparing the SEM pictures for each group on dentin surface, we see a close resemblance in the widths of all dimples. On the contrary, shallower dimples were observed for the 70% air-ratio group compared to the other groups. However, we observed that both the widths and depths of all dimples on the enamel surface were almost the same. These findings were in line with the results from the measurements of cutting depth.

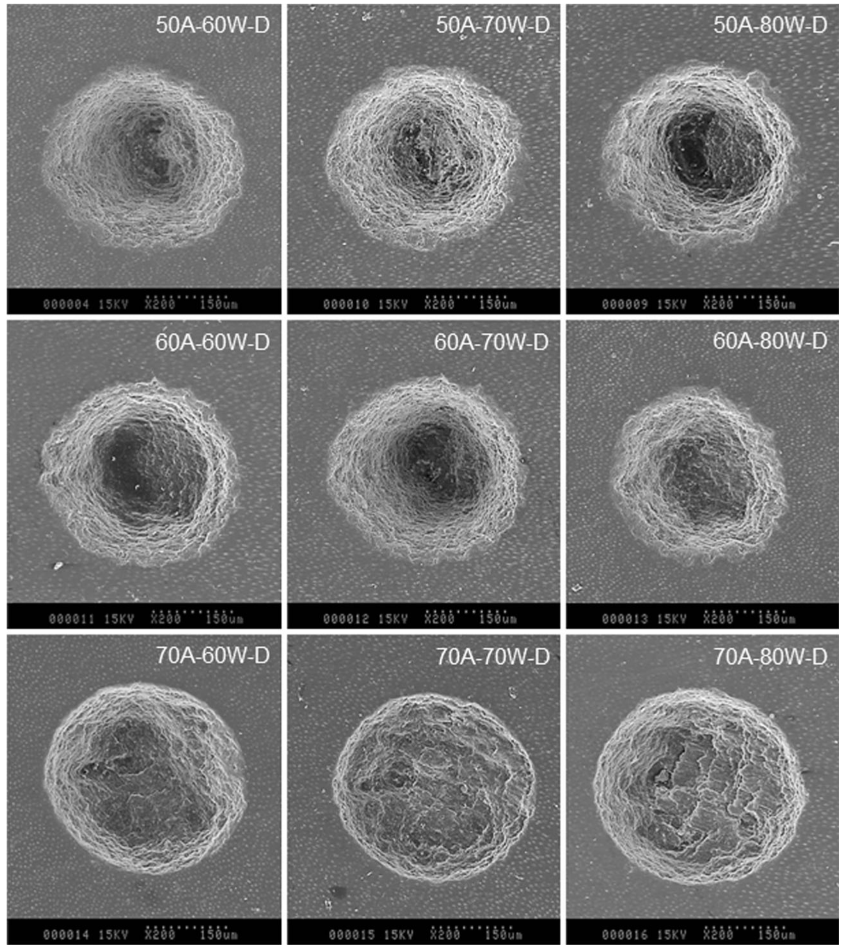

Fig. 3 SEM images of dentin dimples prepared with the laser irradiation accompanied by each percentage of air/water in spray

Because we used an MX5 sapphire pin, which irradiated a laser beam with a focus of 500 μm in diameter and a focal distance of 3–5 mm in our study, the diameters of dimples produced after laser irradiation were assumed to be approximately 500 μm. However, from the results of dimple measurement by means of the scale memory on the SEM pictures in Figs. 2 and 3, the diameters of the dimples on the enamel and dentin surfaces were approximately 380–400 and 400–450 μm, respectively. The laser was irradiated with a focus mode; nevertheless, the diameter of the dimples produced after laser irradiation was actually smaller than 500 μm. Based on this observation, we speculated that the size of the water micro-explosion was smaller than that of the laser beam in focus. Moreover, the discrepancy of the dimple size among the specimens in the same experimental group might be due to the uneven irradiation time for each specimen, because it was not possible to reproducibly control the irradiation time for just 1 s.

With the present study, we demonstrated that the percentage of air/water in spray at a range of relatively high ratio showed no significant effects on enamel cutting efficacy, while it had a significant effect on dentin cutting, using in both cases an Er,Cr:YSGG laser. We had stated as the null hypothesis that the percentage of water/air in spray would not influence the tooth-cutting efficiency of Er,Cr:YSGG laser. Our results show that the null hypothesis was confirmed for dentin, but denied for enamel. Because opening the carious cavity with laser irradiation requires intensive enamel cutting efficacy, the intensity and hertz of laser irradiation could be more important than the percentage of water/air in the spray when cutting the enamel with laser irradiation. Importantly, a careful cutting control is required in clinical situations to excavate numerous types of conditioned dentin including intact, affected, and infected dentin. In other words, delicate handling for dentin cutting when using an Er,Cr:YSGG laser could be realized with a fast setting of the appropriate percentage of water/air in the spray on the operation panel. From our results, in case of removing deep carious dentin near the pulp, a higher percentage of air in the spray would be recommended as our data showed that the amount of dentin ablation was less with a high than with a low percentage of air in the spray. Therefore, we believe that the percentage of air/water in spray should be taken in consideration for the dentin cutting using an Er,Cr:YSGG laser.

Conclusions

Taking in consideration the results as well as the limitations of the present study, we conclude that there was no significant effect of the percentage of air/water in spray on the efficacy of the laser cutting for enamel. On the contrary, we observed a significant effect of the percentage of air in spray on the efficacy of the laser cutting for dentin.

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Compliance with ethical standards

The present study was reviewed and approved by The Human Research Committee of the Nippon Dental University School of Life Dentistry at Niigata (approval number ECNG-H-9).

Conflict of interest The authors declare that they have no competing interests.

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