Study on Dental Hard Tissue Ablation by Er:YAG Laser

- Evalution on Tip Wear -

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Abstract

Purpose: The Er:YAG laser shows excellent performance in the hard tissue cutting, and is used in the clinic. However, cutting efficiency is far inferior to high speed rotation instruments, resulting in increased treatment time. Our study constructed a prototype tip with a spray-type irrigation system to improve cutting efficiency. The prototype tip has become commercially available, and is marketed under the name "CS600F". The present study investigated the cutting volume of human dentin, as well as tip head wear, wear rate, and output using CS600F.

Methods: Sound human molars were used as samples. A smooth surface of dentin was exposed by trimming the tooth with a model trimmer, and was polished with a waterproof abrasive paper up to # 2000-grit. The laser was moved evenly across a 4 mm x 4 mm area on the sample surface by moving the stage 0.5 mm/s, with 10 cycles of laser irradiation. Irradiation distances were set at 0.5, 1.0, and 2.0 mm. The group of samples irradiated with the C600F was defined as the control group, and those irradiated with the CS600F were defined as the atomized spray group. Each sample and tip head was observed under microscope to measure the dentin cutting volume and tip head wear volume, and the tip head wear rate was calculated (n=3). Output power from tip head after irradiation was measured and compared with the output power from tip head set before irradiation.

Results: Dentin cutting volume and tip head wear rate were significantly higher in the atomized spray group compared with the control group. However, tip head wear and output showed no significant differences between the control and atomized spray groups ($p \geqq 0.05$).

Conclusion: Use of the atomized spray irrigation may improve dentin cutting volume without change in the extent of tip wear during dentin cutting. There was no change in tip head output after 10 cycles of irradiation in either the conventional or atomized spray irrigation systems.

Key wards: Er:YAG Laser, hard tissue ablation, Tip Wear

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Introduction

Since Goldman et al.[1] reported the potential of removing caries lesions using a Ruby laser, many studies have been performed on the clinical application of lasers in the dental field. Lasers are currently used in various dental treatments, including endodontic, periodontal, surgical, and conservation treatments[2-7]. In 1989, Hibst and Keller reported that enamel, dentin, and caries can be efficiently cut using a YAG laser[8, 9].

A number of studies have been performed on the Er:YAG laser, demonstrating its clinical effectiveness in endodontic, periodontal, and surgical treatments. The Er:YAG laser minimizes uncomfortable sound and vibration during conservation treatment, therefore putting little stress on the patients and allowing caries treatment without discomfort[10-12]. However, the cutting efficiency of the Er:YAG laser ablation is inferior to high-speed rotation instruments, resulting in increased procedure time. An attempt was made to improve the cutting efficiency by increasing tip head output force and repetition rate (pulse number), but problems remained regarding its effect on the dental pulp. One reason contributing to the reduced cutting efficiency of the Er:YAG laser is the retention of water released from the tip head during drilling in the cavity, resulting in the absorbance of the laser energy and prevention of stable tooth drilling.

Our study investigated the irrigation device used with the Er:YAG setup, and hypothesized that cutting efficiency might be improved by changing the irrigation system to a spray, resulting in a thinner layer of water retention on the cavity surface. A prototype tip with a spray irrigation system was constructed to investigate the cutting efficiency and possible heat damage to the dental pulp. Yokota et al. [13] reported that the prototype tip significantly improved the cutting efficiency compared with a conventional tip, and there was no heat damage to the pulp.

The prototype tip was subsequently made commercially available, marketed as the CS600F (J. Morita Mfg. Corp.) The present study investigated the dentin cutting volume, tip head wear rate, and the change of output power from tip head after irradiation using the CS600F.

Materials and Methods

The Erwin®Adverl (J. Morita Mfg. Corp.) laser oscillation device was used in the present study (Fig. 1). Two irradiation tips, the C600F, with a 600 μm tip diameter and conventional irrigation system (Fig. 2), and the CS600F, with a 600 μm tip diameter and a spray-type irrigation system (Fig. 3) were used. Irradiation conditions were output power of 100 mJ, repetition rate of 10 pps, and water injection volume of 10 ml/m. Output power from tip head was set and monitored using the output measurement device

LaserMate-P (COHERENT).

The following are the experimental methods. The present study was approved by the Medical Ethics Committee of Osaka Dental University (approval number 110844).

1. Sample preparation

Teeth were extracted in the Department of Oral Surgery of Osaka Dental University Hospital, immersed in saline water, and frozen at -40°C. A sound molar without caries (referred to as tooth hereafter) was thawed before each experiment. A smooth surface of dentin was exposed by trimming the human tooth from the crown side using a model trimmer, polished with waterproof abrasive paper up to # 2000-grit, and sonicated for 10 min. The laser irradiation angle against the prepared dentinal surface was 90°, and irradiation distances were set at 0.5, 1.0, and 2.0 mm. A tooth was fixed to the moving stage, and the laser was moved evenly across a 4 mm x 4 mm area on the sample surface by moving the stage 0.5 mm/s.

2. Sample measurement

1) Dentin cutting volume

Each laser-cut sample was observed using a 3D-laser scanning microscope (Keyence VK series, ×100), with a sample number of n=3. 10 cycles of irradiation were performed for each sample, and the dentin cutting volume was measured after 3, 5, and 10 cycles of irradiation.

2) Tip head wear volume

The laser tip both before and after irradiation was observed using a 3D-laser scanning microscope (Keyence VK series, ×200). The sample number for each condition was n =3. Tip head wear before irradiation and after 10 cycles of irradiation were measured, and the difference was defined as the tip head wear volume.

3) Tip head wear rate

Tip head wear rate was defined as the dentin cutting volume per 1 μm^3 of tip head wear volume using the dentin and tip wear volumes measured in 1) and 2).

4) Output power from tip head

Output power from tip head set before irradiation (100 mJ) was not corrected for throughout10cycles irradiation. Output power from tip head was measured after 10 cycles of irradiation, and the result was compared with the set value before irradiation.

3. Statistics

Samples irradiated by the C600F was defined as the control group, and those irradiated by the CS600F was defined as the atomized spray group.

Data were analyzed by two-way ANOVA ($\alpha = 0.05$). Each independent factor was analyzed by one-way ANOVA and Tukey's test ($\alpha = 0.05$).

Results

1. Dentin cutting volumes

Fig. 4 – 6 show the dentin cutting volumes under each condition. Fig. 7 – 9 show representative images of samples under each condition observed by microscope.

1) 3-cycle irradiation

A significant difference was observed in irradiation distance factor and irradiation tip factor, but there was no interaction between two factors. No significant difference was observed between the control and atomized spray groups for each independent factor.

2) 5-cycle irradiation

A significant difference was observed in irradiation distance factor and irradiation tip factor, but there was no interaction between two factors. For each independent factor, cutting volume of the dentin was significantly higher in the atomized spray group compared with the control group between 1.0 and 2.0 mm.

3) 10-cycle irradiation

A significant difference was observed in irradiation distance factor and irradiation tip factor, but there was no interaction between two factors. For each independent factor, the atomized spray group showed a significantly higher result compare with the control group in all conditions.

Visual examination of sample images under each condition showed no differences in the irradiated surfaces between the different tips.

2. Tip head wear

Fig. 10 shows the tip head wear volume. Fig. 11 and 12 show representative images of a laser tip before and after use.

A significant difference was observed in irradiation distance factor and irradiation tip factor, but there was no significant correlation between the two variables. For each independent factor, there was no significant difference between the control and atomized spray group at 0.5 and 1.0 mm irradiation distance, but the atomized spray group showed a significantly higher result compared with the control group at 2.0 mm irradiation distance. Tip head wear volume decreased with increased irradiation distance under all conditions.

A number of small scratches on the laser tip due dentin debris were observed on microscopic images taken after use in both the control and atomized spray groups.

Fig. 13 shows tip head wear rate.

A significant difference was observed in irradiation distance factor and irradiation tip factor, but there was no interaction between two factors. For each independent factor, the atomized spray group showed a significantly higher results compare with the control group in all conditions.

3. Output power from tip head

Fig. 14 shows output power from tip head.

There were no significant differences between the control and atomized spray groups under any of the conditions and each independent factor. Output power from tip head was decreased with an increase in irradiation distance under all conditions.

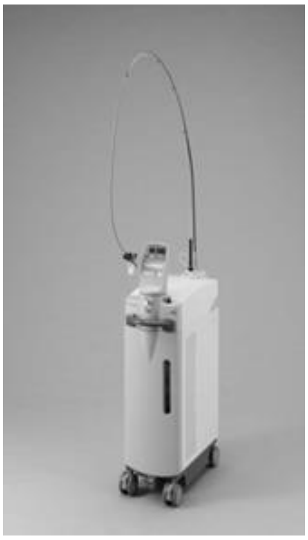

Fig. 1 Erwin® Adverl

Fig. 2 C600F

Fig. 3 CS600F

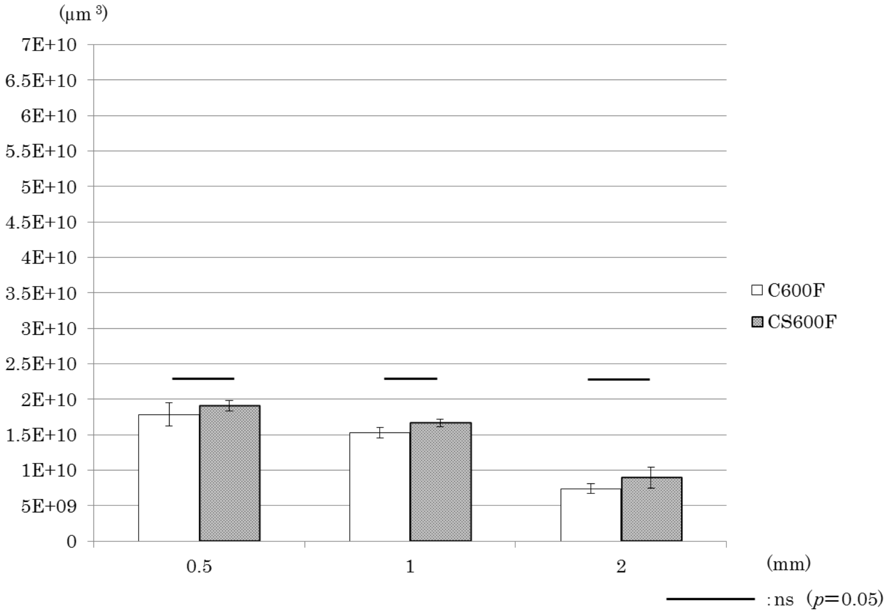

Fig.4 Experiment 1 : Dentin cutting volumes of 3 cycles irradiation
No significant difference was observed between the control and atomized spray groups.

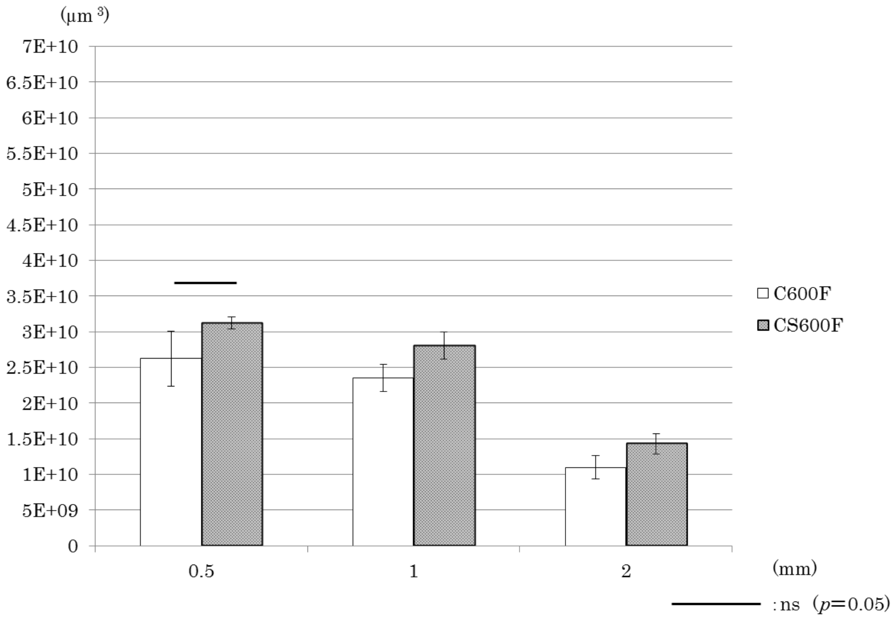

Fig.5 Experiment 1 : Dentin cutting volumes of 5 cycles irradiation
Cutting volume of the dentin was significantly higher in the atomized spray group compared with the control group between 1.0 and 2.0 mm.

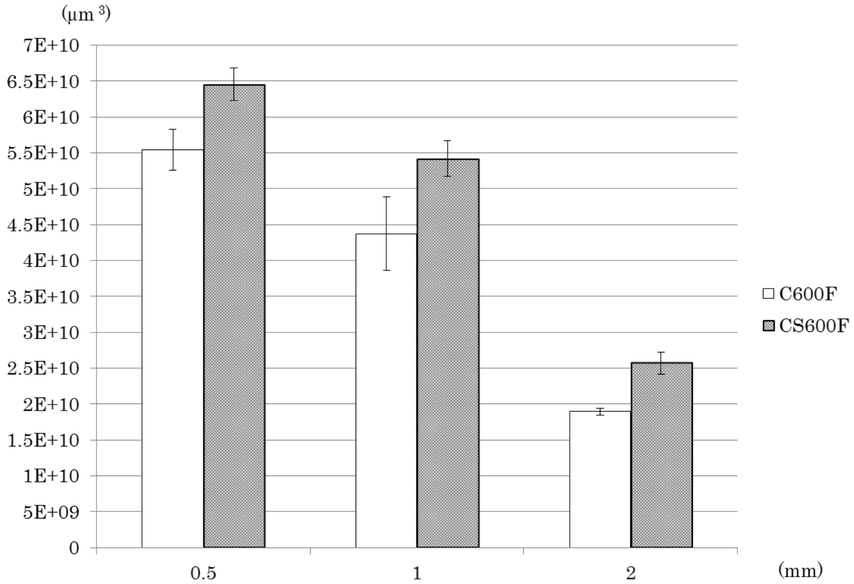

Fig.6 Experiment 1 : Dentin cutting volumes of 10 cycles irradiation
The atomized spray group showed a significantly higher result compare with the control group in all conditions.

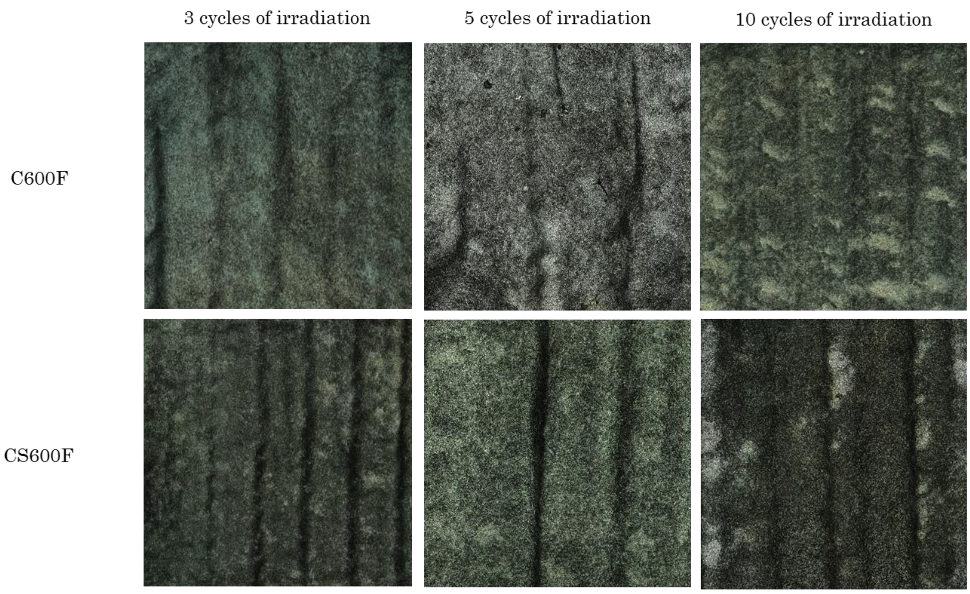

Fig.7 Experiment 1 : Microscope images of samples（×100）
Visual examination of sample images under irradiation distance of 0.5mm condition showed no differences in the irradiated surfaces between the different tips.

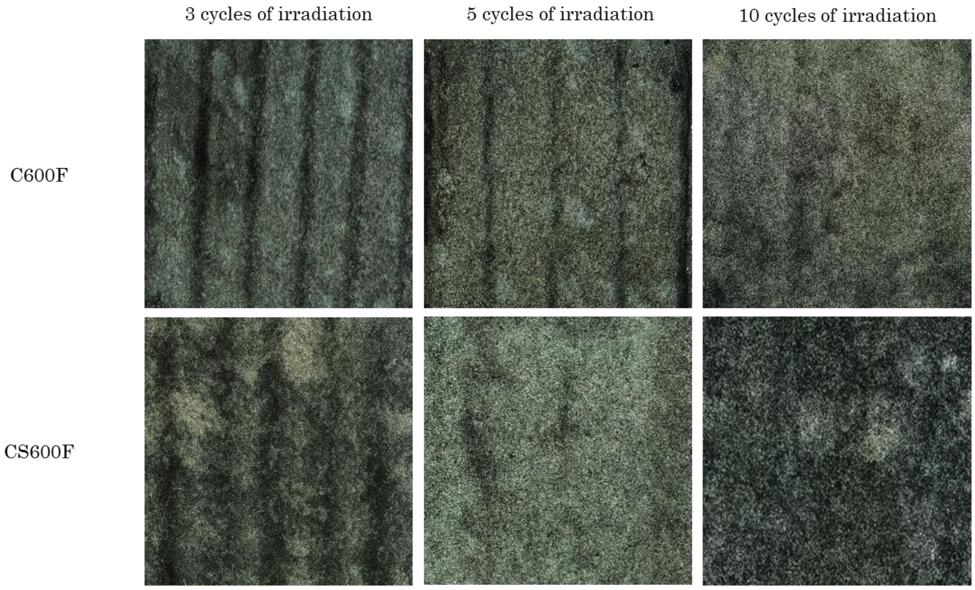

Fig.8 Experiment 1 : Microscope images of samples (×100)
Visual examination of sample images under irradiation distance of 1.0mm condition showed no differences in the irradiated surfaces between the different tips.

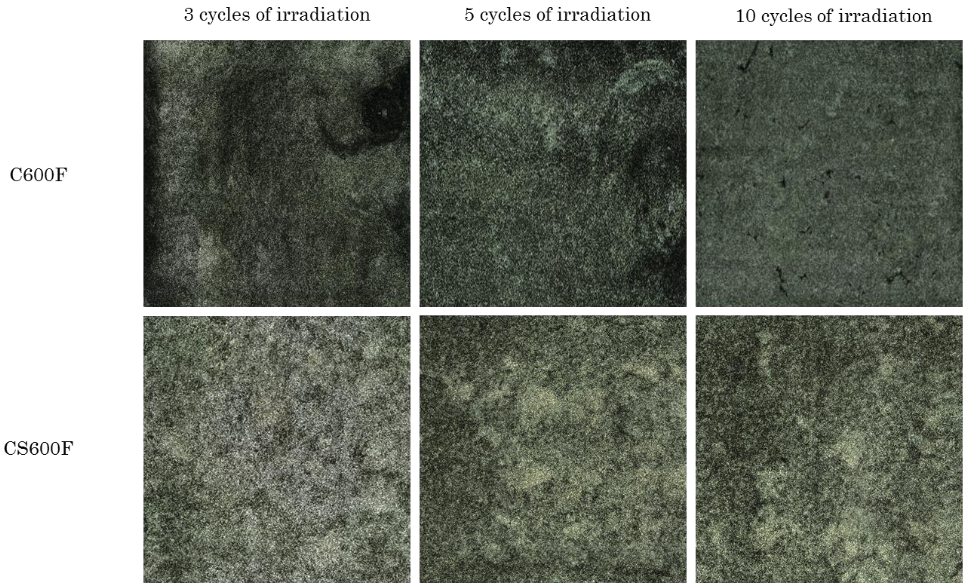

Fig.9 Experiment 1 : Microscope images of samples (×100)
Visual examination of sample images under irradiation distance of 2.0mm condition showed no differences in the irradiated surfaces between the different tips.

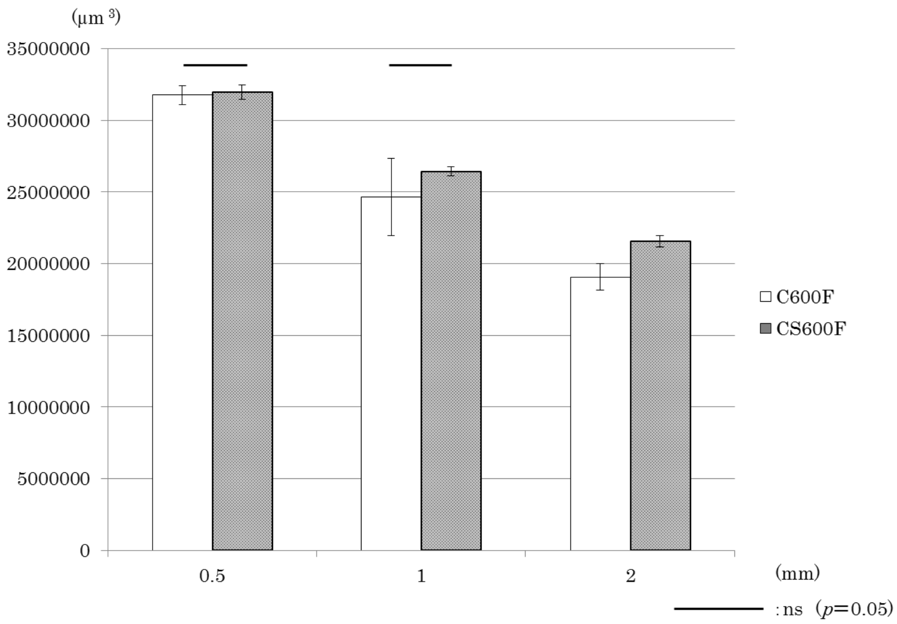

Fig.10 Experiment 2 : Tip head wear volume of 10 cycles irradiation
There was no significant difference between the control and atomized spray group at 0.5 and 1.0 mm irradiation distance, but the atomized spray group showed a significantly higher result compared with the control group at 2.0mm irradiation distance. Tip head wear volume decreased with increased irradiation distance under all conditions.

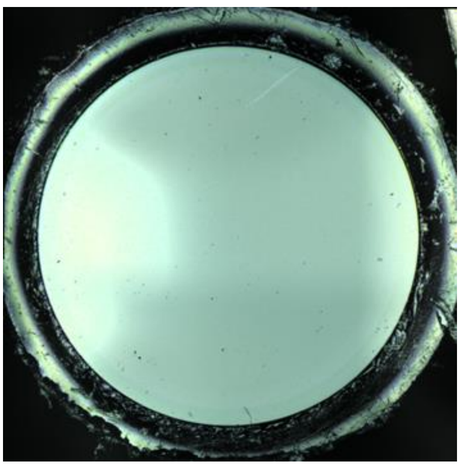

Fig.11 Microscopic image of tip head

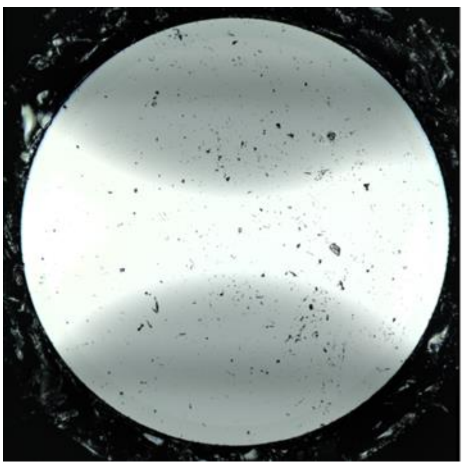

Fig.12 Microscopic image of tip head after use

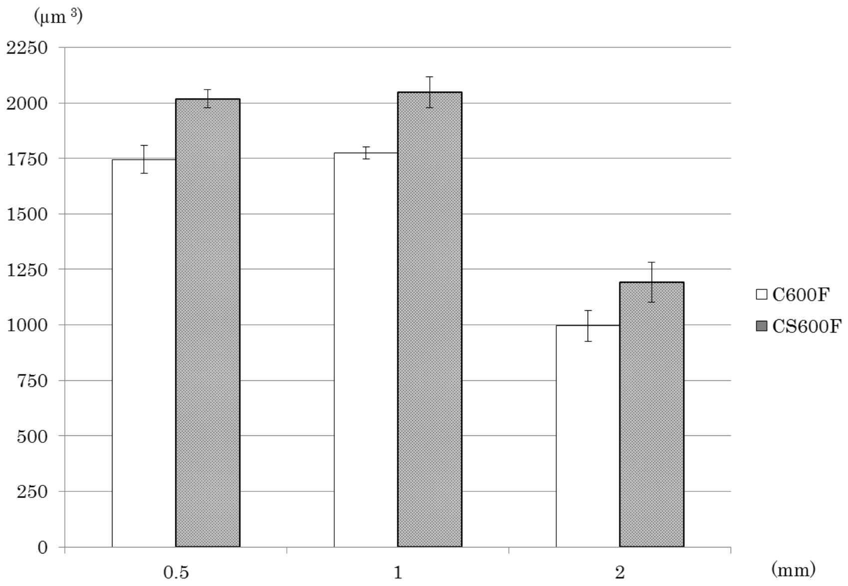

Fig.13 Experiment 2 : Dentin cutting volume/tip wear volume
The atomized spray group showed a significantly higher results compare with the control group in all conditions.

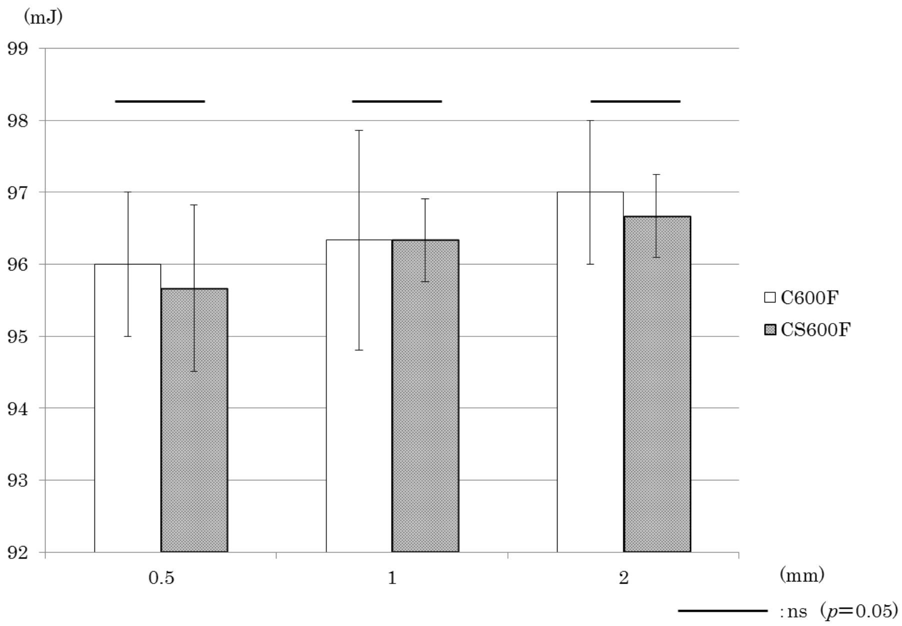

Fig.14 Experiment 3 : Output power from tip head of 10 cycles irradiation
Output power from tip head was decreased with an increase in irradiation distance under all conditions.

Discussion

The oscillation wavelength of the Er: YAG laser is 2.94 µm, which is similar to the maximum absorption band of water[14]. Therefore, irradiation energy is absorbed by the hydroxyl group in both hydroxyapatite, a major component of the hard tissues of teeth, and water. This results in water vapor explosion, and internal collapse of the structure allows cutting of the enamel and dentin due to ablation [14].

One of the characteristics of laser irradiation is that the energy density increases and the intervening water layer becomes thinner with a decrease in distance between the tip head and point of irradiation. As a result, the point of irradiation is bombarded with higher laser energy, and cutting efficiency improves[15]. Laser irradiation methods include the contact method, in which the laser tip and point of irradiation are in contact, and the near-contact method, in which the laser tip and point of irradiation are not in contact[16]. Although the contact method prevents accidental irradiation, and the cutting vibration can be propagated to the fingers, there remain the issues of tip wear and cutting efficiency decrease due to the continuous contact with the tooth[17-19]. Tip wear and decrease in tip output have been reported to be caused by mechanical damage due to contact with the point of irradiation, shock due to the reflection of evaporated material cut from the tooth, laser beam shielding by melting debris, and thermal damage[17-19]. Yokota et al. reported that the cutting efficiency was significantly improved in the atomized spray irrigation system using the near-contact method compared with the conventional irrigation system[13]. When hard tissue is cut by using a laser, not only the cutting efficiency, but also the safety of the method must be considered, particularly when the heat may affect the dental pulp. It is believed that damage in deeper area of tooth substrate is minimal due to absorbance of the laser beam in the superficial layer of the point of irradiation; however, heating of the tooth, and in particular dentin, during irradiation causes dental pulp damage[20]. On the other hand, it was reported that the Er:YAG laser does not cause heat damage in the surrounding tissue if used under water irrigation[21]. The energy of the Er:YAG laser is highly absorbed by water; the absorption efficiency of Er:YAG lasers is approximately 10 times higher compared with CO_2 lasers when used as a laser knife. Therefore, the time required to heat the tissue at the point of irradiation is extremely short. This allows mild temperature increases in the surrounding tissue, resulting in little damage[22-26]. The temperature increase of dentin when irradiated under atomized spray irrigation is estimated to be approximately 2.9°C, which is lower than the temperature change reported to induce dental pulp damage

(5.0°C). Therefore, the use of atomized spray irrigation prevents heat-induced dental pulp damage[13]. Based on this, the present study investigated tip wear under atomized spray irrigation with the near-contact method.

It has been reported that tooth drilling under atomized spray irrigation does not reduce irradiation efficiency, and the avoidance of water accumulating in the cavity results in an improvement of cutting efficiency[13]. Yokota et al. [13] compared the dentin cutting efficiencies between the conventional irrigation system and atomized spray system at irradiation distances of 0.5 and 1.0 mm, and reported that the cutting efficiency was significantly higher using the atomized spray system. In the present study, there was no significant difference in dentin cutting volume between the control and atomized spray groups after 3 and 5 cycles of irradiation at an irradiation distance of 0.5 mm. This is may possibly have been due to accumulation of irrigation water in the 4 x 4 mm cavity in both the control and atomized spray groups. However, because the dentin cutting volume tended to be increased in the atomized spray group compared with the control group, it is possible that cutting volume may be increased in the buccolingual cavity when using optimal vacuum technique, where little water accumulates. The atomized spray group showed significantly higher cutting volume compared with the control group after 5 cycles of irradiation at a distance of 1.0 and 2.0 mm, and showed significantly higher cutting volume compared with the control group under all conditions after 10 cycles of irradiation. These results suggest that the intervening water layer is thinner when cutting dentin under atomized spray irrigation compared with the conventional irrigation system, including under conditions in which the distance between the tip head to the point of irradiation is large, significantly avoiding energy reduction.

It has been reported that the average size of cut dentin pieces evaporated by the laser is approximately 100 µm[27]. Tip wear and decrease in tip output have been reported to be caused by mechanical damage due to contact with the point of irradiation, shock due to the reflection of evaporated material cut from the tooth, laser beam shielding by melting debris, and thermal damage[17-19]. In the present study, tip head wear decreased with an increase in irradiation distance, both in the control and atomized spray groups. This may have been due to the alleviation of mechanical damage to the tip head, and reduction in thermal damage because the scattering and attachment of debris to the tip head was decreased by increased irradiation distance. Tip head wear was higher in the atomized spray group compared with the control group under all conditions. This may have been due to the increased scattering and attachment of dentinal debris to the tip head resultant of improved cutting efficiency using the atomized spray. Tip head wear was significantly higher in the atomized spray group at an irradiation distance of 2.0 mm. However, clinical use of the laser at an irradiation distance of 2.0 mm is unlikely, considering that the cutting efficiency decreased with an increase in irradiation distance, and for prevention of accidental irradiation to the sound tooth surface. Thus, for clinical use, there should be no problem or influence of tip head wear under atomized spray irradiation compared with the conventional irrigation system.

Tip head wear rate was calculated as the dentin cutting volume per 1 μm^3 of tip head wear volume. Significantly higher wear rate was observed in the atomized spray group compared with the control group under all conditions; however, this is likely due to the increased dentin cutting efficiency with use of the atomized spray system.

Quartz fiber tips of the Er:YAG laser are composed of the core, the clad outer surface, and a membrane covering these two layers[28]. The primary component of the core is quartz, and light can travel through the tip without escape from the core due to the higher refraction index compared with the clad. However, the quartz base material of the Er:YAG laser makes it vulnerable to a decrease in head output due to tip wear after long period of irradiation using the contact method[17-19]. Sato et al. [15] reported that there was no decrease in output power from tip head when performing near-contact oblique irradiation for 120 minutes at irradiation angles of 45 and 60°, thus preventing scattered debris deviating the tip head direction, as well as minimizing damage to the tip head and attachment of debris to the tip head. It is thought that a decrease in output power from tip head is caused by mechanical damage due to contact with the point of irradiation, shielding of the laser beam due to attachment and subsequent melting of debris to the tip head, and thermal damage[15,17-19]. One problem of tip head wear is a decrease in head output, which will cause a decrease in cutting efficiency and prolonged treatment time, resulting in increased patient discomfort[28]. Although there was no significant difference in head output between the control and atomized spray groups under any of the conditions, the decrease in head output was alleviated with an increase in irradiation distance. This may have been due to decreases in mechanical damage to the tip head, laser beam shielding due to the attachment and subsequent melting of dentinal debris, and thermal damage. These results suggest that use of atomized spray irrigation has no influence on head output during dentin drilling.

Conclusion

When drilling dentin, the atomized spray irrigation system may improve dentin cutting volume compared with use of the conventional irrigation system, while maintaining a similar degree of tip wear. There was no difference in the change in output power from tip head after 10 cycles of irradiation between the conventional and atomized spray irrigation systems during dentin drilling.

Acknowledgments

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Er:YAG レーザー照射法に関する研究
- チップ損耗性についての検討 -

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抄録

目的：歯の硬組織切削では，Er:YAG レーザーは特に優れた効果を示し，臨床応用されているが，高速回転切削器具と比較し除去効率では到底及ばず，治療時間の延長などが問題となっている．我々の研究グループは切削効率を向上させるため，注水機構を霧状に改良した試作チップを作製し，実験を重ねてきた．今回この試作チップが製品化され，CS600F として発売された．本研究は CS600F を用いてレーザー照射を行い，ヒト象牙質に対する切削体積量，チップ先端損耗体積，チップ先端損耗率および先端出力への影響について検討した．

方法：被験歯として健全ヒト大臼歯を用い，象牙質までモデルトリマーにて面出しを行い，耐水研磨紙にて#2000 まで研磨を行った後，0.5mm/s でムービングステージを移動させながら 4mm×4mm の範囲に均一にレーザー照射を 10 回行った．レーザー照射は試料までの距離を 0.5，1.0 および 2.0 mm に規定した．C600F にてレーザー照射を行った群をコントロール群，CS600F にてレーザー照射を行った群を霧状噴霧群とした．各試料および各照射チップをレーザーマイクロスコープにて観察し，象牙質切削体積量およびチップ先端損耗体積量を計測し，チップ先端損耗率を算出した（n＝3）．また，照射後の先端出力を計測し，照射前に規定した先端出力と比較した．

結果：象牙質切削体積量およびチップ先端損耗率ではすべての条件でコントロール群と比べ霧状噴霧群が有意に高い値を示し，チップ先端損耗体積および先端出力ではコントロール群と霧状噴霧群間で有意な差は認められなかった（p=0.05）．

結論：象牙質切削において，霧状噴霧注水は，チップの損耗状態は変わらずに象牙質切削体積量を向上させることが示唆された．また，従来の注水機構と霧状噴霧注水ともに，10 回照射後も先端出力の変化は認められなかった．

キーワード：Er:YAG レーザー，硬組織切削，チップ損耗性

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