Study on Dental Hard Tissue Ablation by Er: YAG Laser

—Evaluation on Tip Wear—

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Abstract

Purpose: The Er: YAG laser shows excellent performance in hard tissue cutting, and is used in clinical dentistry. However, the cutting efficiency is far inferior to high-speed rotation devices, resulting in increased treatment time. Our study constructed a prototype tip with a spray-type irradiation system to improve the 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 the tip head wear, wear rate, and output using the CS600F.

Methods: Sound human molars were used as samples. A smooth dentin surface was exposed by trimming the tooth with a model trimmer, and then polishing the surface with waterproof abrasive paper up to 2000 grit. The laser was moved evenly across a 4×4 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 20 mm. Samples irradiated with the C600F were 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 a 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 the tip head after irradiation was measured and compared with the output power from the 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 two groups (p≥0.05).

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

Key words: Er: YAG laser, hard tissue ablation, tip wear

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Introduction

Ever since Goldman et al. reported the possibility of removing caries lesions by means of a ruby laser, extensive research has been carried out on the application of lasers in clinical dentistry. Lasers are currently used in various dental procedures, including endodontic, periodontal, surgical, and conservation treatment. In 1989, Hibst and Keller reported that enamel, dentin, and cavities can be efficiently cut using a YAG laser.

Numerous studies have been performed on the Er:YAG laser, demonstrating its clinical effectiveness in endodontic, periodontal, and surgical treatment. The Er:YAG laser minimizes unpleasant sounds and vibration during conservation treatment, thereby reducing patient stress and allowing cavities to be cut without discomfort. However, the cutting efficiency of Er:YAG laser ablation is inferior to high-speed rotation devices, resulting in increased procedure time. An attempt was made to improve the cutting efficiency by increasing the tip head output force and repetition rate (pulse number), but problems remained regarding the effect on 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 laser energy and prevention of stable tooth drilling.

Our study investigated the irrigation device used with the Er:YAG setup, and hypothesized that the 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. 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 change in output power from the 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 were used: the C600F, with a 600 μm tip diameter and conventional irrigation system (Fig. 2), and the CS600F, with a 600 μm tip diameter and spray-type irrigation system (Fig. 3). Irradiation conditions were output power of 100 mJ, repetition rate of 10 pps, and water injection volume of 10 ml/m. Output power from the tip head was set and monitored using the output measurement device LaserMate-P (Coherent Inc.).

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 at 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 dentin surface was exposed by trimming the human tooth from the crown side using a model trimmer and polished with waterproof abrasive paper up to 2000 grit, followed by sonication for 10 min. The laser irradiation angle against the prepared dentin surface was 90°, and the 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 × 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. Ten cycles of irradiation were performed for each sample, and the dentin cutting volume was measured after 3, 5, and 10 cycles.

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 was measured before irradiation and after 10 cycles of irradiation, and the difference was defined as the tip head wear volume.
control group, and those irradiated by the CS600F were defined as the atomized spray group. Data was analyzed by two-way ANOVA (α = 0.05). Each independent factor was analyzed by one-way ANOVA and Tukey’s test (α = 0.05).

Results

1. Dentin cutting volume

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

1) 3-cycle irradiation

A significant difference was observed in the irradiation distance factor and irradiation tip factor, but there was no correlation between the 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 the irradiation distance factor and irradiation tip factor, but there was no correlation between the two factors. For each independent factor, the dentin cutting volume was significantly higher in the atomized spray group compared with the control group at an irradiation distance between 1.0 and 20 mm.

3) 10-cycle irradiation

A significant difference was observed in the irradiation distance factor and irradiation tip factor, but there was no correlation between the two factors. For each independent factor, the dentin cutting volume was significantly higher in the atomized spray group compared with the control group at an irradiation distance between 1.0 and 20 mm.
Fig. 5  Experiment 1: Dentin cutting volume after 5 cycles of irradiation
Cutting volume of the dentin was significantly higher in the atomized spray group compared with the control group at an irradiation distance between 1.0 and 20 mm.

Fig. 6  Experiment 1: Dentin cutting volume after 10 cycles of irradiation
The atomized spray group showed significantly higher results compared with the control group under all conditions.

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

tion distance factor and irradiation tip factor, but there was no correlation between the two factors. For each independent factor, the atomized spray group showed significantly higher results compared with the control group under all conditions.

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

Visual examination of sample images under irradiation distance of 1.0 mm showed no differences in the irradiated surfaces between the different tips.

Fig. 9  Experiment 1: Microscopic images of samples (×100, irradiation distance of 2.0 mm)

Visual examination of sample images under irradiation distance of 2.0 mm showed no differences in the irradiated surfaces between the different tips.
2. Tip head wear

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

A significant difference was observed in the irradiation distance factor and irradiation tip factor, but there was no significant correlation between the two variables. For each independent factor, there was no signifi-

cant 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 irra-
diation distance. Tip head wear volume decreased with increased irradiation distance under all conditions.

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

Figure 12 shows the tip head wear rate.

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

3. Output power from tip head

Figure 13 shows the output power from the tip head.

There were no significant differences between the control and atomized spray groups under any of the conditions and for each independent factor. Output power from the tip head 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\(^\text{14}\). Therefore, irradiation energy is absorbed by the hydroxyl group in both hydroxyapa-
tite, a major component of the hard tissues of teeth, and water. This results in a water vapor explosion, and internal collapse of the structure allows cutting of the enamel and dentin due to ablation\(^\text{44}\).

One of the characteristics of laser irradiation is that the energy density increases and the intervening water layer becomes thinner with a decrease in the distance between the tip head and the point of irradiation. As a result, the point of irradiation is bombarded with higher laser energy, and the cutting efficiency improves\(^\text{15}\). 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\(^\text{16}\). 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 reduced cutting efficiency due to the continuous contact with the tooth\(^\text{17-19}\). Reported causes of tip wear and decrease in tip output are 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\(^\text{17-19}\). Yokota et al\(^\text{33}\), 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. 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 the deeper areas of the 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\(^\text{20}\). 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\(^\text{21}\).

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\(^\text{22-26}\). 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\(^\text{13}\). Based on this, the present study investigated tip wear under atomized spray irrigation using 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 improved cutting efficiency\(^\text{13}\). Yokota

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**Fig. 12**  Experiment 2: Dentin cutting volume/tip wear volume

The atomized spray group showed significantly higher results compared with the control group under all conditions.

**Fig. 13**  Experiment 3: Output power from tip head of 10 cycles irradiation

Output power from the tip head decreased with an increase in irradiation distance under all conditions.
et al. compared the dentin cutting efficiency 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 possibly due to the accumulation of irrigation water in the $4 \times 4$ mm cavity in both the control and atomized spray groups. However, because the dentin cutting volume tended to be higher in the atomized spray group compared with the control group, it is possible that the cutting volume may be increased in the buccolingual cavity when using the optimal vacuum technique, where little water accumulates. The atomized spray group showed a 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 a 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 and 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 $\mu$m. Reported causes of tip wear and decrease in tip output are 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. In the present study, tip head wear decreased with an increase in irradiation distance, in both 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 the increase in 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 as a result 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 20 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 $1\mu$m$^3$ of tip head wear volume. A 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 the 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. The primary component of the core is quartz, and light can travel through the tip without escaping 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 periods of irradiation using the contact method. Sato et al. reported that there was no decrease in output power from the tip head when performing near-contact oblique irradiation for 120 min at irradiation angles of 45 and 60°, thus preventing a deviation in tip head direction from scattered debris, as well as minimizing damage and/or attachment of debris to the tip head. It is thought that a decrease in output power from the 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. One of the problems 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. 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 a decrease 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 the 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 the dentin cutting volume compared with using the conventional irrigation system, while maintaining a similar degree of tip wear. There was no difference in the change in output power from the tip head after 10 cycles of irradiation between the conventional and atomized spray irrigation systems during dentin drilling.

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Er：YAG レーザー照射法に関する研究

一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。われわれの研究グループは、切削効率を向上させるため、注水機構を新製し改良した試作チップを製作し、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。

材料と方法：被験歯として健全ヒト臼歯を用い、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、0.5 mm/s でムービングステージを移動させながら 4×4 mm の範囲に一回にレーザー照射を 10 回行った。レーザー照射は試料までの距離を 0.5, 1.0 mm および 2.0 mm に規定した。

CS600F 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。

成績：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