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Effect of Optical Wedge Rotary on Ablation Efficiency of Femtosecond Laser on Dental Hard Tissue and Restorative Materials

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Abstract

Objective: Femtosecond laser (fs-laser) is a novel tooth preparation tool but its ablation efficiency is insufficient. The purpose is to establish a new fs-laser tooth ablation method based on a dual-wedges path ablation system, and explore the efficiency of tooth hard tissue and dental restorative materials ablation.
Materials and methods: Extracted third molars, pure titanium, cobalt-chromium alloy, gold alloy, and 3Y-zirconia were prepared into samples. These samples were rotary ablated by an fs-laser with dual-wedges. The wavelength was 1030 nm and the pulse duration was 250 fsec. Laser parameters were set as a repetition frequency of 25 kHz, the power percentages as 50% for dental tissues, and 60% for restorative materials. The optical wedge angle was set as 0°, 20°, 40°, 60°, and 80° for restorative materials, 0°, 20°, 30°, 40°, and 60° for enamel, and 0°, 10°, 20°, 30°, and 40°for dentin. Three times of ablation was processed at each parameter to obtain total 90 ablation microcavities of 6 kinds of materials. The diameter, depth, and volume of microcavities were measured by confocal laser microscopy and plotted against optical-wedge-angle in curves of different materials. One-way analysis of variance (ANOVA) was used to test whether the ablation efficiency between different angles was statistically significant.
Results: The ablation efficiency of each material at different optical-wedge-angle was statistically significant ($p < 0.05$) and tends to be correlated. For dental hard tissue, the enamel ablation efficiency was 208.1 times and dentin ablation efficiency were 65.2 times than before when the wedge angle was 40°. For pure titanium, zirconia, cobalt-chromium, and gold alloys, the ablation efficiencies were 3.1, 10.7, 81.5, and 128.8 times than before when the rotation angle was 80°.
Conclusions: The ablation efficiency of dental hard tissues and restorative materials was significantly increased with the increase of laser oblique incidence angle.
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Keywords: femtosecond laser, ablation efficiency, enamel, dentin, restorative materials, optical wedge

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Introduction

FOR TOOTH DEFECTS caused by caries, trauma, abrasion, erosion, and developmental dysmorphia, tooth preparation is necessary before filling. The traditional preparation by turbine drill is the common way in clinic. With the development of digital technology, robot manufacturing and laser technology, laser tooth preparation is booming. Since the introduction of laser into the research and application of tooth preparation, it has been favored because of its safety and comfort.[1,2]

The laser pulse width directly affects the ablation thermal effect.[3] Femtosecond laser (fs-laser) is a kind of ultrashort pulse laser with a pulse width of 10^{-15} sec, a power intensity of 10^{14} W/cm^2. It is sufficient to make the bound electrons of the insulator be stripped into free states and the optical breakdown occurs, so as to realize the ablation of the material.[4] Due to its ultra short pulse duration, the material will be directly carried away by plasma before the heat can spread around, which can be regarded as ''cold'' processing.[4–6] It is considered to be the least tissue thermal damage laser. These characteristics make fs-laser a unique high-precision micro-nano ablation tool.[3,7–15] Recently scholars have studied the application of fs-laser on teeth, and found that fs-laser pulses can progressively remove enamel and dentin with an acceptable precision and accuracy, with little or no observed thermal effects.[16]

However, the ablation of fs-laser is considered to be inefficient. Sun et al. prepared cavities by an fs-laser at 800 nm on enamel and dentin, and the measured ablation efficiencies is, respectively, 5.7×10^{-3} mm^3/s and 56.0×10^{-3} mm^3/s.[17] Chen et al. found that there is an optimal fluence value for ablation efficiency of the fs-laser with a wavelength of 800 nm.[18] When the fluence was 8.85 J/cm^2, the enamel ablation efficiency reached the maximum. When the fluence was 2.21 J/cm^2, the dentin ablation efficiency reached the maximum. Serbin et al. also measured a positive correlation between ablation efficiency and fluence.[3]

Cangueiro and Vilar used fs-laser to ablate bovine tibia and found that scanning speed and effective pulse number were positively correlated with ablation efficiency.[19] Use the fs-laser with a repeated frequency of 2 kHz at 1030 nm and the scanning speed of 10 mm/s by water-cooling, the maximum ablation efficiency can be up to 1.4 mm^3/min.

To improve the ablation efficiency, researchers have also tried various methods, such as using lasers with high repetition frequency or acid etching pretreatment of tooth tissue. Petrov et al. obtained high ablation efficiencies of 2.85 and 3.33 mm^3/s for enamel and dentin using a commercial fs-laser with a repetition rate of 500 kHz and a power of 5 W at 1030 nm.[20] Loganathan et al. attempted to etch the tooth tissues before ablation and obtained significantly improved the ablation efficiency by an 800 nm fs-laser.[21] However, some results showed that when the repetition frequency was too high, thermal damage and mechanical damage would occur.[22]

Therefore, it is generally accepted that the ablation efficiency achieved by most fs-lasers is lower than turbine drills. Efficiency improvement is still one of the topics. In this study, we used fs-laser with optical wedges to ablate dental hard tissues and restorative materials to explore whether the ablation efficiency could be improved.[23,24] The null hypothesis was that the ablation efficiencies have no difference between different wedge angles.

Materials and Methods

Laser path construction

In this experiment, the laser path was set up: a fiber ultrashort pulse laser (YACTO-FL50; Hangzhou Yi Li, China) was used, with a wavelength of 1030 nm, a max repetition frequency of 500 kHz, and a pulse width of 250 fsec. The laser is emitted from the generator and passes through the optical gate, attenuating plate, focusing system, and mirror successively. At the end, the optical wedge scanning processing module of Zhongke Micro Precision Company is added. The whole optical rotation system is mainly driven by a high-speed rotating motor to synchronous high-speed rotation of a deflection module and lateral displacement module to achieve the control of laser processing beam trajectory, so that the fs-laser enters the module after a series of offset to achieve the rotary ablation.

Finally, a plano-convex lens with a focal length of 150 mm is used to focus the fs-laser beam onto the target sample fixed on the 3D mobile platform. The parallel plate rotary beam scanning module consists of a deflection wedge and a displacement wedge.

Parameters calculation

The calculation formula of the output spot diameter (ω_0) of the laser beam after passing through the focusing system is:

$$\omega_0 = \frac{4M^2\lambda f}{\pi D}$$

Among them, λ is the laser wavelength of 1030 nm, F is the focal length of the plane convex lens used, 150 mm, D is the diameter of the input beam, 10 mm, M^2 is the beam fixed parameter, according to the manufacturer's design of the optical path, and M^2 is a constant value of 1.2.

Laser fluence (F) can be calculated by the following formula:

$$F = \frac{P}{k\pi\left(\frac{\omega_0}{2}\right)^2}$$

Where P is the value manually read on the power meter (843-R; Newport) during the processing, K is the repetition frequency, and ω_0 is the output spot diameter calculated in the above equation.

Sample preparation

Four commonly used dental restorative materials, gold alloy (Minigold, Ivoclar Vivadent), cobalt-chromium alloy (Wironit, Bremer, Germany), pure titanium (TA2, Rijin, Japan), and 3Y-zirconia porcelain block (SHT, Aidite, China) were used to prepare cuboid samples. Several impacted third molars extracted from the oral surgical department of Peking University Hospital of Stomatology were collected and immediately put into 0.01% thymol solution. A diamond wire cutter (STX-202; Kejing, China)

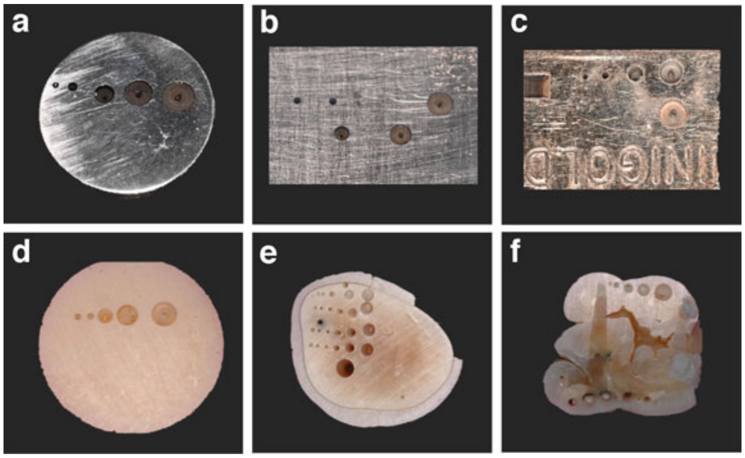

FIG. 1. The images of dental restorative materials and dental hard tissues after fs-laser ablation when the wedge angle increases successively. Cobalt-chromium alloy **(a)**, pure titanium **(b)**, gold alloy, **(c)** 3Y-zirconia **(d)**, dentin **(e)**, and enamel **(f)**. fs-laser, femtosecond laser.

was used to make two parallel cuts in the crown of the tooth perpendicular to the long axis of the tooth to obtain a dental sample with a thickness of 3 mm.

The dentin was exposed on the upper surface of the sample, and the outer ring of the dentin was coated with enamel. The upper surfaces of all tooth and restorative materials samples were applied to a water sandpaper polishing machine (M-Prep 5™; Allied) using mesh sizes of 320, 600, 800, 1000, 1500, 2000, and 3000 sandpaper under a stream of water until smooth. The tooth samples were stored in thymol solution before and after the laser ablation experiment to maintain a certain hydration state to prevent drying and cracking. This study was approved by the Ethics Committee of Peking University Hospital of Stomatology (no. PKUSSIRB-201949124).

Laser wedge rotary ablation

The fs-laser parameters were set to a repetition rate of 25 kHz and a pulse energy percentage of 60%. The number of scanning layers was set as 50, the scanning time of each layer was 1 sec, the laser Z-axis dropped by 0.01 mm after each layer was scanned, and the optical wedge angle was adjusted in the range of 0° to 80° during the processing. 0° is used as a blank control to compare with the ablation where the laser beam is incident diagonally on the sample surface. The laser optical wedge rotary ablation was performed on six materials (Fig. 1), namely pure titanium, cobalt-chromium alloy, gold alloy, 3Y-zirconia porcelain block, enamel, and dentin. Each material was ablated by five different angles (Table 1). Each parameter was repeated three times, and a total of 90 laser ablation holes were obtained.

Table 1. The Parameters of Femtosecond Laser to Explore the Effect of Wedge Angles on Ablation Efficiency of Dental Hard Tissue and Prosthetic Materials

Materials	*Percentage of Pulse energy (%)*	*Repetition frequency (k)*	*Scanning layers*	*Wedge angles (°)*
Prosthetic materials	60	25	50	0, 20, 40, 60, 80
Dentin	50	25	50	0, 10, 20, 30, 40
Enamel	50	25	50	0, 20, 30, 40, 60

Diameter, depth, volume measurement, and ablation efficiency calculation

All the samples were cleaned in an ultrasonic washing machine (DR-MH20, Derry, China) for 40 min to remove the plasma attached to the surface. The diameter, depth, and volume of the cavities were measured with a laser confocal microscope (VK-X00, Keyence, Japan). In this experiment, the laser ablation efficiency is defined as the volume of the sample ablation by the laser per unit time. The ablation efficiency of each microcavity was calculated, and the mean value and standard deviation of three replicates of each angle were calculated. The ablation diameters, depths, and efficiencies of four restorative materials, enamel, and dentin were plotted to observe their changing trends. The ratio of the maximum ablation efficiency during the change of the optical wedge angle to the ablation efficiency when the laser is vertically incident is calculated to visually express the improvement of the ablation efficiency.

Statistical analysis

All ablation efficiency data were input into SPSS software, and Shapiro-Wilk and Levene were used to test the normality and homogeneity of variance of the data, respectively. If the data conform to normal distribution and homogeneity of variance, one-way analysis of variance (ANOVA) was used, and the least significant difference (LSD) pairwise comparison was performed. If the data did not conform to normal distribution, the Kruskal–Wallis H test was used, and the Bonferroni method was used for pairwise comparison after adjustment. If the data were inconsistent, Brown-Forsythe test was used, and Dunnett's T3

Table 2. The Relationship of Percentage of Pulse Energy and Power

Percentage of pulse energy	*Power*	*Fluence*
50%	1.70 W	7.77 J/cm^2
60%	2.04 W	9.32 J/cm^2

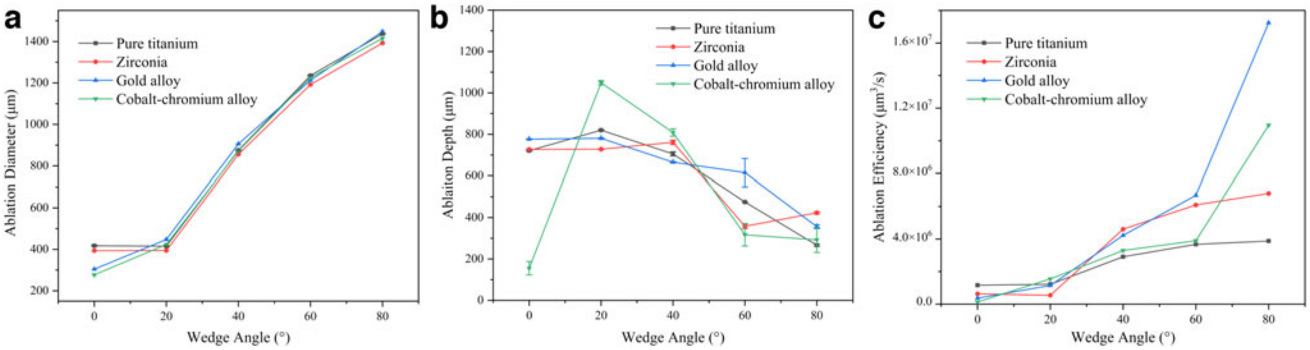

FIG. 2. The diameter **(a)**, depth **(b)**, and ablation efficiency **(c)** of four kinds of restorative materials by different fs-laser wedge angles.

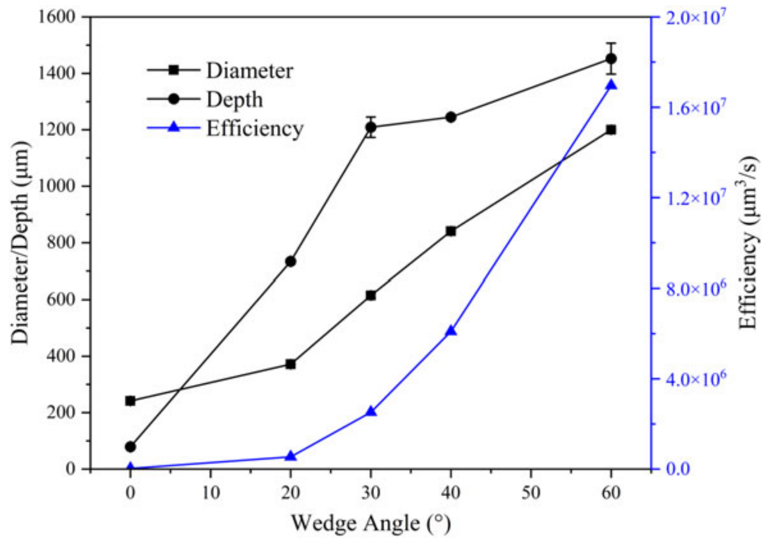

FIG. 3. The diameter, depth, and ablation efficiency of enamel by different fs-laser wedge angles.

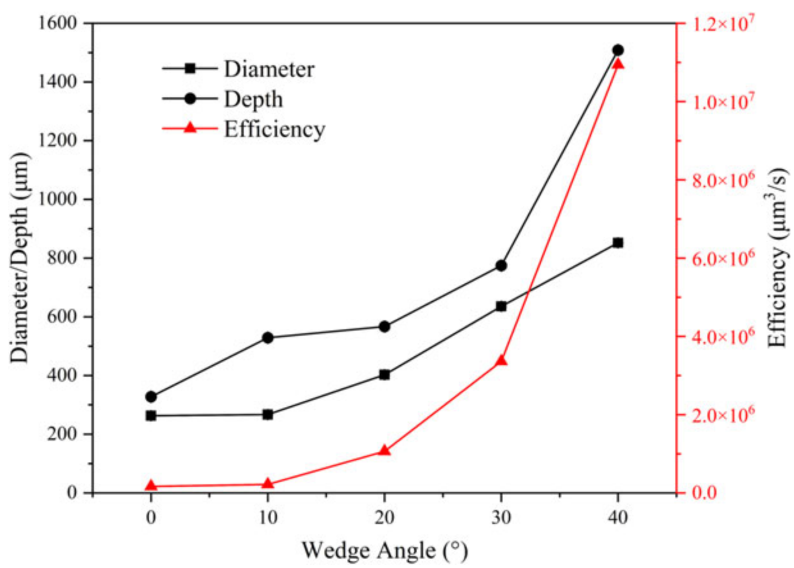

FIG. 4. The diameter, depth, and ablation efficiency of dentin by different fs-laser wedge angles.

was performed for post hoc multiple comparisons. The null hypothesis is that there is no difference in ablation efficiency at different optical wedge angles.

Results

Calculation results of spot diameter and fluence

The focused spot diameter (ω_0) was calculated as 23.6 μm. When the repetition rate is 50 kHz and the set value of the laser pulse energy percentage is 60%, the laser power was 2.04 W, and the fluence (F) was calculated as 9.32 J/cm^2. The relationship between the percentage of power and the fluence used in this experiment is shown in Table 2.

Ablation efficiency of the restorative materials

Among the restorative materials, the ablation diameters have been found to be positively related to optical wedge angles, and the specific variation trend was shown in Fig. 2a. The trend of four kinds of restorative material curves is very consistent. The diameters charge with the angles. When the optical wedge angle reached 80°, the ablation diameters of gold alloy, pure titanium, cobalt-chromium alloy, and zirconia reached 1448.33 ± 5.7, 1437.20 ± 1.90, 1415.40 ± 11.95, and 1392.90 ± 2.09 μm, respectively. It is 3.5–4.7 times of the ablation diameter when the laser is vertically incident.

As the number wedge angles increased, the ablation depth first increased and then decreased. The detailed results are shown in Fig. 2b. The deepest depth of zirconia was obtained at 40°, whereas other three materials reached the deepest at 20°. After that, the depth decreased as the angle continued to increase. After 50 sec ablation, the maximum ablation depths of gold alloy, pure titanium, cobalt-chromium alloy, and zirconia were 780.60 ± 1.84, 819.73 ± 1.96, 1048.90 ± 10.36, and 760.97 ± 10.66 μm, respectively.

Ablation efficiency continued to increase with the increase of optical wedge angle, as shown in Fig. 2c. The results show that when the wedge angle is 80°, the ablation efficiency of the four materials is increased by 65.2–208.1 times compared with that when the laser is vertically incident.

Ablation efficiency of dental hard tissue

For the tooth hard tissue, the ablation diameter, depth, and efficiency of the tooth showed an increasing trend with the increase of the optical wedge angle under the laser parameters. The change of diameter is basically the same as that of the restorative materials while the depth increases substantially with the angle. At the same time, the ablation efficiency also increases rapidly. The specific changes of enamel and dentin ablation effects are shown in Figs. 3 and 4. When the wedge angle was 40°, the ablation efficiency of enamel and dentin was 208.1 times and 65.2 times than at 0°, respectively.

Table 3. Brown-Forsythe Test of the Ablation Efficiency of Prosthetic Materials and Dental Hard Tissues

Materials	*Statistics*	*f1*	*f2*	p
Gold alloy	1.84×10^3	4	2.979	0.000
Pure titanium	8.94×10^3	4	2.432	0.000
Cobalt-chromium alloy	30.45	4	2.201	0.025
Zirconia	2.13×10^4	4	2.212	0.000
Dentin	8.61×10^4	4	3.982	0.000
Enamel	1.00×10^3	4	2.101	0.001

Table 4. Dunnett's T3 Test of the Enamel Ablation Efficiency by Different Wedge Angles

Angle 1 (I)	*Angle 2 (J)*	*Difference of means (I-J)*	*Standard error*	p
0	20	-5.09×10^5	3.56×10^3	0.000
0	30	-2.38×10^6	7.03×10^4	0.003
0	40	-6.07×10^6	3.72×10^4	0.000
0	60	-1.74×10^7	5.01×10^5	0.003
20	30	-1.87×10^6	7.04×10^4	0.005
20	40	-5.56×10^6	3.74×10^4	0.000
20	60	-1.69×10^7	5.01×10^5	0.003
30	40	-3.69×10^6	7.96×10^4	0.000
30	60	-1.50×10^7	5.06×10^5	0.004
40	60	1.13×10^7	5.03×10^5	0.007

Statistical analysis

Shapiro-Wilk test showed that the data were normally distributed ($p > 0.05$). However, Levene test showed that the variance was not homogeneous ($p < 0.05$). Therefore, Brown-Forsyth was used for group difference analysis, and Dunnett's T3 was used for post hoc multiple comparisons. Brown-Forsythe test results showed that, for each material, there was a statistically significant difference in ablation efficiency between different optical wedge angles ($p < 0.05$), as shown in Table 3. The null hypothesis was rejected. The pairwise comparison results of Dunnett's T3 (as is shown in Supplementary Tables S1–S4) showed that, except for cobalt-chromium alloy, the ablation efficiencies of the other three restorative materials at the angle of 80° were statistically significantly different from those at other angles ($p < 0.05$). For enamel and dentin, the pairwise comparison results (Tables 4 and 5) showed statistically significant differences between the efficiencies at each ablation angle ($p < 0.05$).

Discussion

In this study, the use of optical wedges to rotate the fs-laser beam obliquely into samples significantly improves the ablation efficiency of the dental hard tissue and restorative materials. The null hypothesis was rejected. Also, the ablation

Table 5. Dunnett's T3 Test of the Dentin Ablation Efficiency by Different Wedge Angles

Angle 1 (I)	*Angle 2 (J)*	*Difference of means (I-J)*	*Standard error*	p
0	10	-4.88×10^4	2.53×10^3	0.010
0	20	-8.88×10^5	4.85×10^3	0.000
0	30	-3.15×10^6	2.12×10^4	0.000
0	40	-1.08×10^7	2.69×10^4	0.000
10	20	-8.40×10^5	5.46×10^3	0.000
10	30	-3.10×10^6	2.13×10^4	0.000
10	40	-1.07×10^7	2.71×10^4	0.000
20	30	-2.26×10^6	2.17×10^4	0.000
20	40	-9.91×10^6	2.74×10^4	0.000
30	40	-7.65×10^6	3.43×10^4	0.000

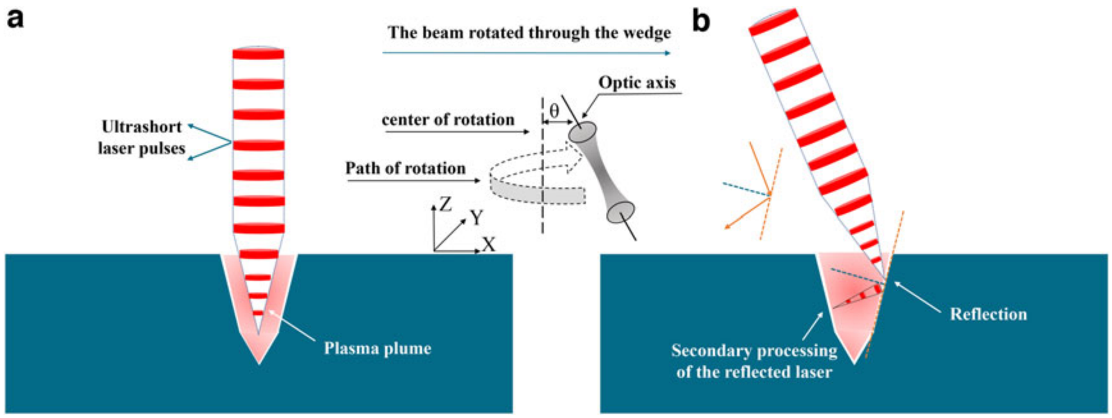

FIG. 5. Schematic of the mechanism of fs-laser machining before **(a)** and after **(b)** using optical wedges.

efficiency increases with the increase of the oblique incidence angle. For the dental hard tissue, when the wedge angles increased, not only the ablation diameter but also the ablation depth and efficiency increased. The possible reason is that the oblique laser beam will be reflected after entering the material surface, and then the beam reflected to the bottom will continue to remove materials by secondary processing, as is shown in Fig. 5. When the same fs-laser parameters are used for ablation, the ablation diameter increases with the increase of the beam incidence angle, and so, the plasma expulsion is easier.

However, the ablation of restorative materials presented a different pattern, especially metal materials. The mechanism of fs-laser ablation is complex. For metal materials, there is no need for electron excitation because of the free electrons around metal surface. Under the ablation of fs-laser, the free electrons produce high-frequency vibration, and the energy generated by vibration is transferred to the lattice through phonon relaxation, resulting in phase explosion and plasma splashing. When the laser fluence is $>10^8$ W/cm^2, the photo-induced plasma will be ejected in the opposite direction of the laser incident to form a plasma cloud, and then the plasma shielding effect will appear.[25,26]

The peripheral high-density plasma expands, continues to absorb laser energy, blocks the laser from reaching the target surface of the material, cuts off the coupling between laser and tooth tissue, and reduces the ablation effect. With the increasing beam angle, the region of bottom ablated by laser reflected by lateral wall enhanced, lead to more plasma deposited at the bottom, thus strengthened the plasma shielding effect. As a result, the ablation depth reduced. Compared with the ablation of tooth tissue, the removal depth of metal materials did not continue to increase with the increase of the optical wedge angle. It can be concluded that fs-laser has obvious advantages in accurately ablating metal materials of which the ablation threshold is much lower than that of dental hard tissue. However, the plasma shielding effect will highly reduce the metal ablation efficiency, especially when the depth increases.

Other study also measured the efficiency. Sun et al. prepared cavities by an fs-laser at 800 nm on enamel and dentin, and the measured ablation efficiencies are, respectively, 5.7×10^{-3} mm^3/s and 56.0×10^{-3} mm^3/s.[17] Chen et al. found that fluence, line spacing and ablation depth all have significant effects on ablation efficiency of the fs-laser with a wavelength of 800 nm.[18] In a certain range, with the decrease of fluence and the increase of line spacing and ablation depth, the ablation efficiency will reduce accordingly. Kerse et al. used a 42.5 GHz fs-laser at 1035 nm with high internal pulse repeated frequency to perform dentin ablation experiments, and the ablation efficiency was up to 3 mm^3/min.[27] This study used a novel fs-laser with high internal pulse repeated frequency and achieved good effect. However, optical wedges were not involved in their studies.

This study has some potential limitations. The maximum optical wedge angles used to ablate enamel and dentin were only 60° and 40°. Although the ablation efficiency still improved with the increase of angles, angles wider than 60° in enamel and 40° in dentin would lead to dental sample penetration, making inaccurate results. Due to the limitation of the thickness of human enamel and dentin samples, the optical wedge angle was not further increased in the study. However, for the restorative materials, the sample thickness available can be much thicker. Therefore, the max wedge angle was increased to 80° to observe the further changes. In addition, this *in vitro* study only provides the basis for parameter selection. When considering clinic applications, safety and feasibility must be taken into consideration.

In this experiment, the efficiency of fs-laser ablation tooth tissue by optical wedge can be increased by 65–208 times. The ablation efficiency can be further improved if the optical wedge can be combinedly used with vibration mirrors to optimize the optical path in the future. Our study only explored the effect of optical wedge to the simple fs-laser optical path on the ablation of teeth, and the ablation form was rough cylinder, without designing complex cavity form. The future research direction is to prepare cavity forms combined with the translation platform controlling the sample movement to meet the clinical needs.

Authors' Contributions

X.Z.: investigation and writing- original draft preparation. X.Y.: data curation and software. Y.W.: visualization and investigation. Y.S.: project administration, software, and validation. C.D.: writing—review and editing. H.C.: supervision and funding acquisition.

Code Availability

No additional codes are available.

Author Disclosure Statement

No competing financial interests exist.

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Supplementary Material

Supplementary Table S1
Supplementary Table S2
Supplementary Table S3
Supplementary Table S4

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