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Abstract. The objective was to study the relationship between laser fluence and ablation efficiency of a femtosecond laser with a Gaussian-shaped pulse used to ablate dentin and enamel for prosthodontic tooth preparation. A diode-pumped thin-disk femtosecond laser with wavelength of 1025 nm and pulse width of 400 fs was used for the ablation of dentin and enamel. The laser spot was guided in a line on the dentin and enamel surfaces to form a groove-shaped ablation zone under a series of laser pulse energies. The width and volume of the ablated line were measured under a three-dimensional confocal microscope to calculate the ablation efficiency. Ablation efficiency for dentin reached a maximum value of 0.020 $\mathrm{mm^3/J}$ when the laser fluence was set at 6.51 $\mathrm{J/cm^2}$. For enamel, the maximum ablation efficiency was 0.009 $\mathrm{mm^3/J}$ at a fluence of 7.59 $\mathrm{J/cm^2}$. Ablation efficiency of the femtosecond laser on dentin and enamel is closely related to the laser fluence and may reach a maximum when the laser fluence is set to an appropriate value. [DOI: 10.1117/1.JBO.20.2.028004]

Keywords: femtosecond laser; tooth preparation; prosthodontics; enamel; dentin; efficiency.

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1 Introduction

With the development of digital dental technology (digital impressions, CAD/CAM technology, etc.), automated solutions for the production of dental restorations are becoming more sophisticated.[1–4] Currently, tooth preparation in prosthodontics can only be done manually and its accuracy cannot be guaranteed. Therefore, techniques for automated tooth preparation are being studied. However, in such a small space, automated tooth preparation in the oral cavity is hard to achieve with a mechanical grinding bur, which means putting a miniaturized three (or more)-axis computerized numerical control (CNC) machine into the mouth. Moreover, the CNC machine must be firmly fixed to the teeth to overcome the reaction force generated during tooth preparation. Other than mechanical grinding methods, the application of lasers coupled with digital control systems may provide solutions to these problems. For example, a laser beam production device and a laser motion control device can be placed outside of the mouth, with a small light-guiding device to direct the laser beam into the oral cavity.[5] The laser spot then scans across the surface of teeth causing ablation. During tooth preparation, the relative position of the teeth and the ablation device can be easily maintained with a simple fixing unit, as the laser does not produce a significant reaction force.

Of the variety of available lasers used to ablate dental hard tissues, the femtosecond laser is one that can reach a high degree of accuracy while producing less heat than others during the processing,[6–8] thus meeting certain basic requirements of tooth preparation in prosthodontics. As the pulse width of a femtosecond laser is shorter than the target material's thermal relaxation time, dentin or enamel is ionized into plasma before thermal diffusion takes place,[9] greatly reducing the generation of thermal effects. Indeed, the rising of the intrapulpal temperature was observed to be less than 5°C with air cooling.[8,10] Microcracks, carbonization and recrystallizations, which are commonly produced during microsecond or nanosecond laser ablation, were scarcely observed on the surface of dentin or enamel after femtosecond laser ablation.[8,11–13] Furthermore, the dentin smear layer produced by the traditional high-speed bur grinding blocks dentinal tubules, thus requiring treatment via either total etching with phosphoric acid or its incorporation to the hybrid layer by using self-etching adhesives to achieve the necessary bonding strength.[11,13–15] Conversely, after femtosecond laser irradiation, dentinal tubules remain open with no smear layer produced, which benefits bonding with the prosthesis.[5,14] However, in clinical practice, tooth preparation needs to be completed within a certain period of time. Keeping the mouth open for a long time can be very discomforting for the patient, and a long operation time reduces the doctor's efficiency. Therefore, the rapidity of femtosecond lasers used for tooth preparation is one of the essential elements that determine its use in clinical application.

The surface morphologies of dentin and enamel after ablation by femtosecond lasers were observed in previous studies,[12,14,16,17] though the ablation rapidity was rarely studied. Ablation rapidity of a femtosecond laser can be evaluated according to its "ablation rate" (AR), which was defined in

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this article as the ablation volume per unit of time (mm^3/s). In this article, another parameter, "ablation efficiency" (AE), was defined as the ablation volume per unit of energy (mm^3/J). Ablation rate can, therefore, be represented as the product of ablation efficiency and laser power (P): $AR = P \times AE$. According to this equation, to improve ablation rate, it is necessary to increase either laser power or ablation efficiency. However, the difficulty and cost of manufacturing a femtosecond laser increases substantially when more laser power is needed. Therefore, it is important to attempt to increase ablation efficiency. Laser fluence is closely related to the ablation depth and ablation volume of a femtosecond laser pulse;[8,12,13,18,19] therefore, a high correlation between laser fluence and ablation efficiency is expected. The aim of this article is to study the relationship between laser fluence and ablation efficiency of a femtosecond laser and to optimize laser fluence to achieve greater ablation efficiency.

2 Materials and Methods

2.1 *Sample Preparation*

Premolars extracted for orthodontic reasons at the Oral and Maxillofacial Surgery Department of Peking University School of Stomatology were used in this study. After immersion and disinfection in neutral buffered formalin for 2 weeks, these teeth were cross-sectioned with a diamond wire saw (STX-202, Shenyangkejing Instrument Co. Ltd., China) into 1.5-mm thick pieces where the dentin was surrounded by a circle of peripheral enamel. The samples were manually polished with 300, 600, and 1200 grit water sandpapers, subjected to ultrasonic cleaning for 20 min and then stored in sterile saline.

2.2 *Experimental Methods*

The laser used in this study was a Yb:KYW diode-pumped thin-disk femtosecond laser (JenLas® D2.fs, Jena, Germany) which emitted a Gaussian beam with a wavelength of 1025 nm, pulse width of 400 fs, repeat frequency of 30 to 200 kHz, and average power of 0 to 4 W. Repeat frequency and average power could be adjusted by the supporting software. The laser beam passed through a galvanometer system (GO2-YAG-12-22-D, Beijing JCZ Technology Co. Ltd., China) and focused on the samples fixed on a platform. The diameter of the focused spot was estimated to be 25 to 40 μm, and repeat frequency was set at 30 kHz. The laser spot was swept in a line programmed by EasyCad V1 software (Beijing JCZ Co. Ltd., China) with a sweeping length of 5 mm and velocity of 360 mm/s. The sweep line passed across the dentin-enamel junction with half of the laser spot on the dentin surface and the other half on the enamel surface. The laser was set to ablate using nine different pulse energies at different areas of the sample (Table 1). The laser spot swept back and forth several times in one line, though the sweeping duration in each direction was reduced for higher laser energies to control for ablation depth. The experiment was repeated four times under each pulse energy. Following ablation, the samples were subjected to ultrasonic cleaning and observed under a three-dimensional (3-D) profile measurement laser microscope (VK-X100/X200, Keyence, Japan) (width display resolution, 0.001 μm; height display resolution, 0.0005 μm; 50× objective lens) to measure the line width and ablation volume. The ablation rate under each pulse energy was calculated as the quotient of the ablation volume and the corresponding ablation duration. The ablation efficiency was calculated as the quotient of the ablation rate and average laser power.

Table 1 Experimental parameters of laser sweeping (sweeping velocity = 360 mm/s)

Number	Sweeping times	Pulse energy (μJ)
G1	20	7.67
G2	20	11.50
G3	20	15.33
G4	20	19.17
G5	10	23.00
G6	10	26.83
G7	10	30.67
G8	10	34.50
G9	10	38.33

2.3 *Mathematical Model*

The ablation threshold and the radius of the laser beam waist could be calculated based on the diameter of the ablated areas and the corresponding incident laser pulse energy.[20] The characteristics of a femtosecond laser beam can be attributed to a Gaussian beam, and the spatial distribution of laser fluence $\varphi(r)$ follows a Gaussian distribution[20]

$$\varphi(r) = \varphi_0 e^{-2r^2/\omega_0^2}, \tag{1}$$

where r is the distance to the center of the beam (μm), φ_0 is the fluence in the center of the beam (J/cm^2), and ω_0 is the radius of the beam waist (μm). The relationship between laser pulse energy and fluence is[20]

$$\varphi_0 = \frac{2E_p}{\pi\omega_0^2}, \tag{2}$$

where Ep is the pulse energy of the femtosecond laser (J). Ablation occurs when the laser fluence reaches the ablation threshold φ_{th}[20]

$$D^2 = 2\omega_0^2 \ln\left(\frac{\varphi_0}{\varphi_{th}}\right), \tag{3}$$

where D is the diameter of the ablation zone (μm). Equation (2) could be substituted into Eq. (3)

$$\begin{aligned} D^2 &= 2\omega_0^2 \ln \frac{2E_p}{\pi\omega_0^2\varphi_{th}} \\ &= 2\omega_0^2 \ln 2 + 2\omega_0^2 \ln E_p - 2\omega_0^2 \ln \pi\omega_0^2\varphi_{th}. \end{aligned} \tag{4}$$

Equation (4) shows a linear relationship between D^2 and $\ln E_p$

$$D^2 = K_D \cdot \ln E_p + B, \tag{5}$$

where K_D represents the slope of the linear fit of $D^2 \sim \ln E_p$ and B represents the intercept

$$K_D = 2\omega_0^2, \tag{6}$$

$$B = 2\omega_0^2 \ln 2 - 2\omega_0^2 \ln \pi\omega_0^2\varphi_{\mathrm{th}}. \tag{7}$$

Values of ω_0 and φ_{th} could be solved from Eqs. (6) and (7)

$$\omega_0 = \sqrt{\frac{K_D}{2}}, \tag{8}$$

$$\varphi_{\mathrm{th}} = e^{\frac{2\omega_0^2 \ln 2 - B}{2\omega_0^2}} / \pi\omega_0^2. \tag{9}$$

Once the value of ω_0 is determined, the laser fluence (φ_0) under each pulse energy (E_p) could be calculated from Eq. (2), so as to correspond to each AE measured in Sec. 2.2.

3 Result

The sweeping line on the enamel surface under a pulse energy (E_p) of 7.67 μJ showed a vague dark zone with discontinuous boundaries and only superficial damage [Fig. 1(a)]. A groove-shaped ablation zone with a certain depth was produced following irradiation of enamel and dentin under a pulse energy of 11.50 μJ [Fig. 1(b) and 1(c)]. The 3-D profiles of the ablation zones are shown in Fig. 2.

There was a linear relationship between D^2 and $\ln E_p$ for both dentin and enamel (Fig. 3). The beam waist radius (ω_0) was calculated to be 15 μm and the ablation thresholds (φ_{th}) of dentin and enamel were 1.18 and 1.38 J/cm^2, respectively.

As the laser spot scanned across the surface of a sample, when a series of laser pulses fell on the surface, there was some degree of overlap between one pulse and the next, effectively resulting in ablation of a single spot by multiple pulses during a single sweep. The approximate relation derived for the effective number of pulses (N_{eff}) incident along the ablated groove is given[21]

$$N_{\mathrm{eff}} = \sqrt{\frac{\pi}{2}} \cdot \frac{\omega_0 f}{v}, \tag{10}$$

where $f = 30$ kHz was the laser repetition rate and $v = 360$ mm/s was the scanning velocity of the laser spot. N_{eff} was thus calculated to be 1.57.

AEs under each laser fluence (φ_0) are shown in Fig. 4. Experimentally measured data showed that AE first increased with the increase of laser fluence, reaching a maximum of 0.020 and 0.009 mm^3/J at fluences of 6.51 and 7.59 J/cm^2 for dentin and enamel, respectively; raising laser fluence beyond these values began to decrease AE.

4 Discussion

A femtosecond laser is an ultrashort pulse laser with a pulse width in the femtosecond time scale. The interaction between a femtosecond laser and biological tissue is called "plasma-mediated ablation."[22] When the laser intensity exceeds 10^{13} to 10^{14} W/cm^2, ablation proceeds via an electrostatic mechanism; specifically, a high concentration of electrons is excited in the medium, causing the material to generate plasma evaporation;[22,23] the laser-induced plasma then absorbs the laser energy very quickly, causing the rapid removal, or ablation, of the target tissue. The ablation threshold is affected by the laser pulse width, wavelength and pulse numbers, among other factors, and was reported to be 0.6 to 2.2 J/cm^2 for enamel and 0.3 to 1.4 J/cm^2 for dentin in related studies.[8,12,16–18,24,25] For multiple pulse ablation, the decrease of the ablation threshold with an increasing number of pulses was observed in many previous studies[26–29] and explained to be incubation effects.[27,28] In this study, a multipulse ablation with 1.57 pulses per spot size was estimated, thus the ablation threshold measured should be slightly lower than a single pulse ablation, according to the incubation effects.

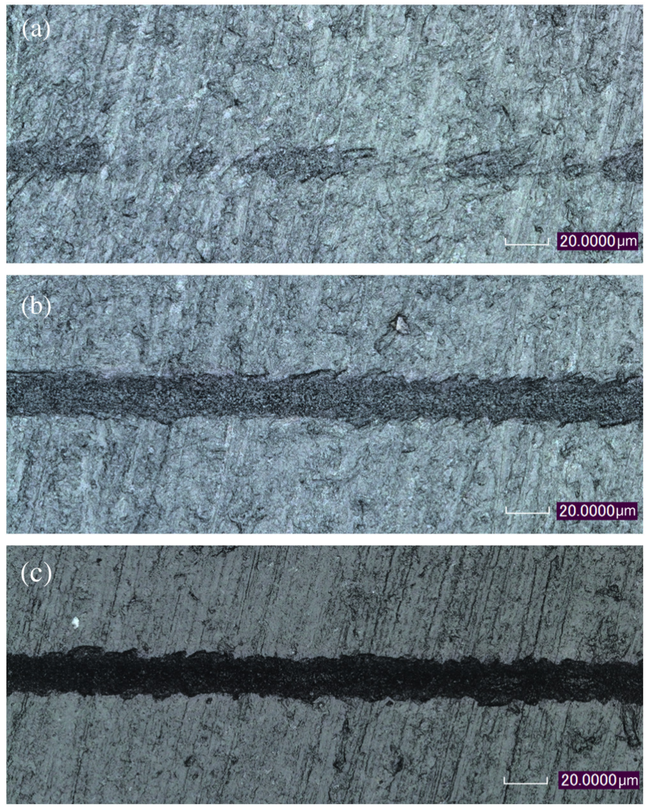

Fig. 1 Tooth surfaces after irradiation by a femtosecond laser under a sweeping velocity of 360 mm/s (20 passes): (a) enamel, pulse energy 7.67 μJ, shallow damage in noncontiguous zones observed; (b) enamel, pulse energy 11.50 μJ; (c) dentin, pulse energy 11.50 μJ. Three-dimensional (3-D) profile measurement laser microscope (50X).

In another study, dentin and enamel were ablated at a laser fluence reaching the ablation threshold (φ_{th}).[16] When a low laser fluence was applied, only a small proportion in the center of the laser spot could cause ablation, resulting in a rather lower AE. However, when the laser fluence is increased far beyond the ablation threshold (φ_{th}), a "plasma shielding" effect[12] may take place. Furthermore, some studies found femtosecond laser ablation of dental hard tissue with a high fluence led to an accumulation of plasma.[12,19] This accumulated plasma can be absorbed or reflected by the incoming laser photons, causing a shielding effect, which might also decrease ablation efficiency.

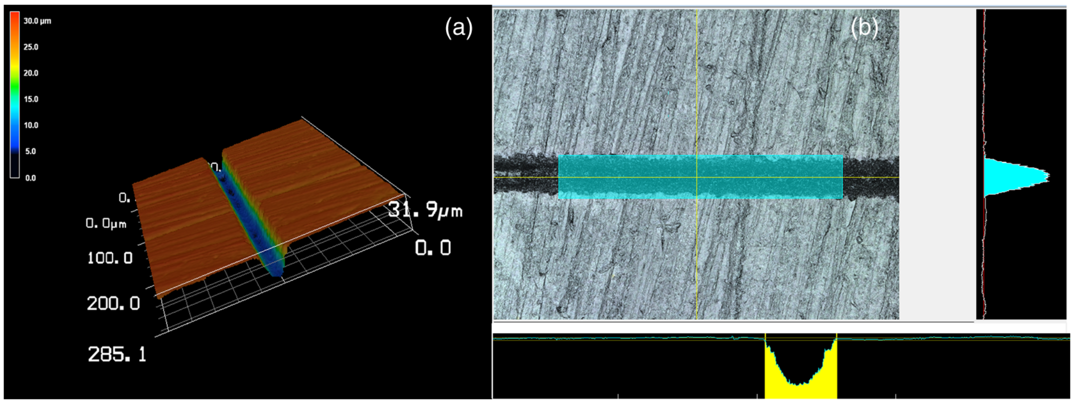

Fig. 2 3-D measurement of ablated sample (pulse energy 15.33 μJ, laser sweeping velocity 360 mm/s, 20 times): (a) 3-D view of the ablated zone; (b) measurement of the volume and width of the ablated zone (blue region); 3-D profile measurement laser microscope (50×).

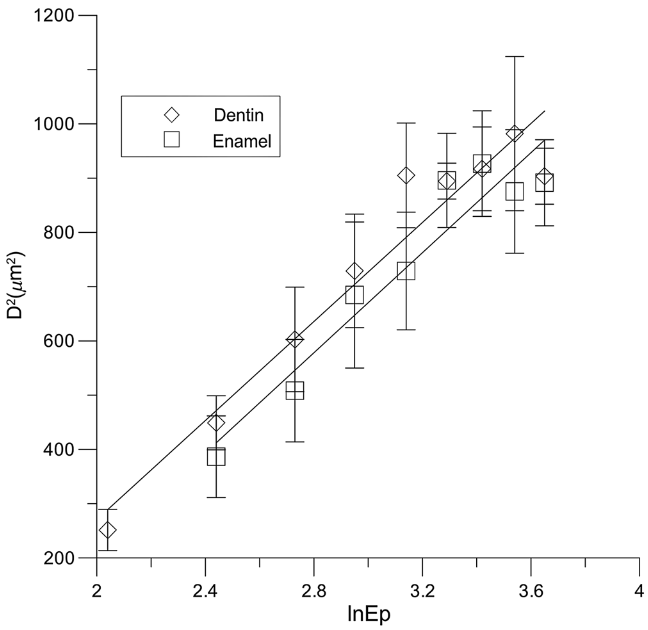

Fig. 3 Linear relationship between the square of the ablated line width and the natural logarithm of pulse energy for both dentin and enamel.

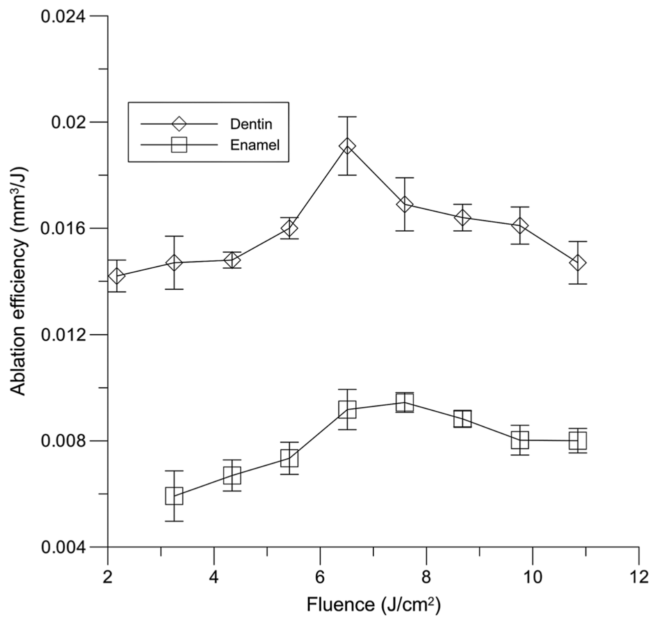

Fig. 4 Relationship between ablation efficiency (AE) and laser fluence.

According to the results of this experiment, the AEs of dentin and enamel are related to laser fluence, suggesting that it is possible to find an appropriate fluence value to achieve a higher AE. Approximately 300 mm^3 of dental hard tissue, mostly enamel, is ground out during tooth preparation for a typical full metal crown of a molar, and ablation rate is calculated to be up to 0.17 mm^3/s to complete the tooth preparation work within half an hour. In this experiment, as the maximum AE for enamel was found to reach 0.009 mm^3/J, a femtosecond laser with an average power of 20 W could meet these requirements. A lower power could suffice if the pattern of the ablation path is improved such that the laser only produces a fissure between the unwanted tissue and abutment tooth, peeling off the unwanted dentin or enamel without extra ablation.

Zach and Cohen[30] found that a 5.6°C change in intrapulpal temperature can cause necrosis of 15% of the pulp tissue, and a 16.7°C change can cause necrosis of 100% of the pulp tissue. Rode et al.[8] measured the rise in intrapulpal temperature during femtosecond laser (150 fs, 1 W, 1000 Hz, and maximum laser fluence 21 J/cm^2) ablation of the surface of a human premolar to be only ~3°C after a 2-min irradiation. The femtosecond laser used in this experiment had a lower fluence but a much higher repetition rate (30 times) than Rode's, which could have increased intrapulpal temperature. Intrapulpal temperature will, therefore, be measured in a further study. The AE of dentin and enamel may also be affected by the laser wavelength, pulse width, and other parameters, which also requires further study.

5 Conclusion

For a femtosecond laser with a Gaussian-shaped pulse, the AE is closely related to the laser fluence, reaching a maximum value when the laser fluence is appropriately adjusted.

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