A Roughness Study of Ytterbium-Doped Potassium Yttrium Tungstate (YB: KYW) Thin-Disk Femtosecond Ablated Dentin

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Abstract:

Introduction: The aim of this study was to evaluate the morphological changes and quantitatively assess the roughness of dentin after the ablation with a Ytterbium-Doped Potassium Yttrium Tungstate (YB: KYW) thin-disk femtosecond pulsed laser of different fluences, scanning speeds and scanning distances.
Method: Twelve extracted human premolars were sectioned into crowns and roots along the cementum-enamel junction, and then the crowns were cut longitudinally into sheets about 1.5 mm thick with a cutting machine. The dentin samples were fixed on a stage at focus plane. The laser beam was irradiated onto the samples through a galvanometric scanning system, so rectangular movement could be achieved. After ablation, the samples were examined with a scanning electron microscope and laser three-dimensional profile measurement microscope for morphology and roughness study.With increasing laser fluence, dentin samples exhibited more melting and resolidification of dentin as well as debris-like structure and occluded parts of dentinal tubules.
Results: When at the scanning speed of 2400mm/s and scanning distance of 24μm, the surface roughness of dentin ablated with femtosecond pulsed laser decreased significantly and varied between values of dentin surface roughness grinded with two kinds of diamond burs with different grits. When at the scanning speed of 1200mm/s and scanning distance of 12μm, the surface roughness decreased slightly, and the surface roughness of dentin ablated with femtosecond pulsed laser was almost equal to that grinded with a low grit diamond bur.
Conclusion: This study showed that increased laser influence may lead to more collateral damage and lower dentin surface roughness, while scanning speed and scanning distance were also negatively correlated with surface roughness. Adequate parameters should be chosen to achieve therapeutic benefits, and different parameters can result in diverse ablation results.
Keywords: laser; dentin; morphology

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Introduction

Grinding with rotary instruments is the most common used clinical operation for tooth preparation and caries removal. It brings effectivity and efficiency as well as some inevitable drawbacks[1], such as the noise and vibration produced which always make the patients feel scary about the therapy, cooling is indispensable when treating teeth with living pulp, because the heat generated while operating may lead to irreversible pulp damage[2]. Smear layer is also a problem; cavities made with mechanical instruments must subsequently be upgraded to provide anchorage for the restorative materials[3, 4]. To overcome these drawbacks, lasers have been attracting wide attention for being a potential tool in oral medicine[5]. The common used laser sources in dentistry include Carbon Dioxide Laser (CO_2) laser, Neodymium-Doped Yttrium Aluminium Garnet (Nd:YAG) laser, Erbium-Doped Yttrium Aluminum Garnet/ Erbium, Chromium doped Yttrium Scandium Gallium Garnet(Er:YAG/Er,Cr:YSGG) laser and diode laser. Because of the obvious thermal damage like glazing, melting, resolidification and cracks produced by the continuous wave CO_2 laser, Nd:YAG laser, and diode laser when ablating dental hard tissues[6-9], these lasers are mostly used in soft tissue surgery and root cannel system therapy [10, 11]. Meanwhile, Er:YAG laser and Er,Cr:YSGG laser can be highly absorbed by water molecules contained in the dental hard tissues and have been widely used in dental clinic[12-15]. However, the mechanism of the ablation process with these lasers is predominated by microexplosion which can break the hydroxyapatite structure and lead to undesired appearance like microcracks, fragments, charring, fusion, melting and recrystallization[3, 16, 17].

In recent years, some studies have proved that the dental hard tissues can be precisely ablated with a femtosecond laser and minimal collateral damage was observed [18-23]. Most of the surface morphology of femtosecond laser ablated dental tissues observed by scanning electron microscopy revealed the interaction between the femtosecond pulsed laser and tooth structure, the evaluation of ablation results are mostly qualitative and little quantitative data is analyzed. The purpose of this study is to present the difference of ablated dentin surface roughness and morphology with different laser fluences, and provide the basis for the application of femtosecond pulsed laser in oral clinical treatments.

Methods

Sample preparation

Twelve extracted human premolars which were orthodontically indicated for extraction were collected at the Oral and Maxillofacial Surgery Unit of the Peking University Hospital of Stomatology. The teeth were soaked in formalin solution for two weeks after their extraction and sectioned into crowns and roots along the cementum-enamel junction. The crowns were then cut longitudinally into twenty-four sheets about 1.5 mm thick with a cutting machine (STX202, KEJING, Shenyang, China). Subsequently, the dentin sheets were grounded with sandpaper of 600, 800 and 1200 grits and randomly divided into eight groups of three. Then the samples were stored in saline solution to prevent them from drying out until the irradiation began.

Laser radiation

The experiment was performed with a ytterbium-doped potassium yttrium tungstate (Yb:KYW) diode-pumped solid-state thin-disk femtosecond laser (JenLas® D2.fs, Jena, Germany), which produces wavelength of 1025nm and pulses of less than 400fs. This laser system generated an output power of up to 4W, and pulse repetition rate of 30-200 kHz. A pulse repetition rate of 100 kHz was used in this study. The laser beam was focused on the sample surfaces through a galvanometric scanning system (GO2-YAG-12-22-D, JCZ, Beijing, China), with focus distance of 100mm and a focal spot diameter of approximately 24μm. Six groups of samples were treated with laser and the parameters used are demonstrated in Table 1.

The dentin samples were fixed on a stage at focus plane and paralleled lines were irradiated on samples at different fluences (F), scanning speeds (v) and scanning distances (d). The specific fluence was obtained by adjusting the output power. The scanning distance is the movement of laser beam between two scanning lines.

Mechanical preparation

Two other groups were set for surface roughness control. A turbine handpiece (BORALINA, Bien-Air, Bienne, Switzerland) was used at a speed of 310,000 rpm. In group 7, the dentin samples were grinded with a diamond bur (TF-12, MANI, Japan) and dentin samples in group 8 were grinded with another diamond bur (FO-20EF, MANI, Japan).

Table 1. Laser parameters used

Group	Fluence (J/cm^2)	Scanning speed (mm/s)	Scanning distance (μm)
G1	2	2400	24
G2	4	2400	24
G3	8	2400	24
G4	2	1200	12
G5	4	1200	12
G6	8	1200	12

Analysis of samples

Laser 3D profile measurement microscopy

Surface roughness of all samples was measured with a laser 3D measurement microscopy (VK-X200 series, KEYENCE, Japan). The object lens used was of 50× magnification. Surface roughness of each sample was measured three times at three different areas. With SPSS 13.0 for windows, all experimental group data obtained were performed with one-way ANOVA test or Tamhane's T2 test to evaluate whether laser fluence and scanning speed have an effect on dentin surface roughness.

Scanning electron microscopy

Laser irradiated samples were observed under a scanning electron microscopy (SEM) (S-4800, HITACHI, JAPAN). For observation, the samples were coated with a layer of gold using a SEM coating system. Images of the samples were obtained with a secondary electron detector. Multiple images were obtained at representative areas with different magnifications, and all images were saved in Graphics Interchange Format (GIF) format.

Results

Laser 3D profile measurement microscopy

The influence of laser fluence and scanning speed on surface roughness of dentin after femtosecond pulsed laser were studied. Mean surface roughness values and standard deviations are displayed in Table 2 and Figure 1.

The one-way ANOVA of each roughness parameter revealed a significant difference among different fluencies when v=2400 mm/s and d=24µm ($P<0.001$), the surface roughness decreased with increasing laser fluence. No significant difference of Ra existed when v=1200 mm/sand d=12µm ($P>0.05$), while the value decreased slightly when higher fluence was used. A significant difference of

Table 2. Mean surface roughness and standard deviations for each group

Group	Mean ± SD		
	Ra (µm)	Rz (µm)	Rq (µm)
G1	2.41 ± 0.32	26.14 ± 11.56	2.95 ± 0.40
G2	1.83 ± 0.64	20.57 ± 5.28	2.29 ± 0.78
G3	1.15 ± 0.15	16.18 ± 5.97	1.42 ± 0.18
G4	1.96 ± 0.98	18.90 ± 6.26	2.46 ± 1.22
G5	1.12 ± 0.32	15.10 ± 4.02	1.38 ± 0.36
G6	0.98 ± 0.28	15.03 ± 6.72	1.22 ± 0.34
G7	4.20 ± 1.10	20.42 ± 4.37	5.15 ± 1.30
G8	1.11 ± 0.14	20.42 ± 4.37	1.41 ± 0.19

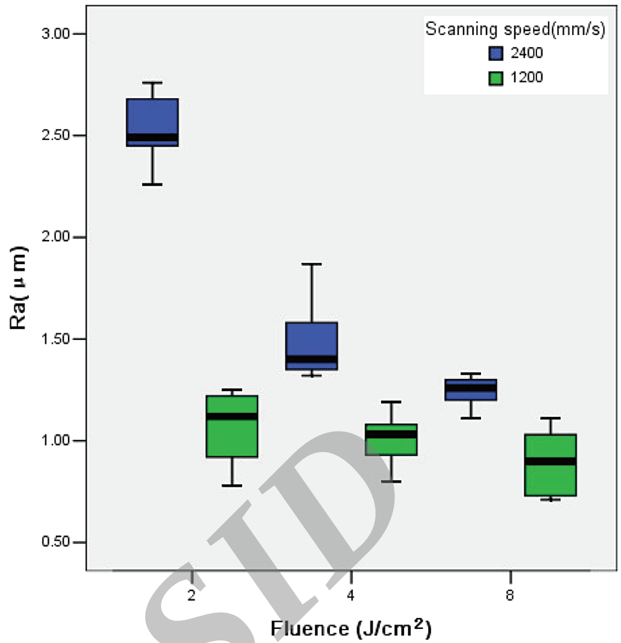

Figure 1. Ra of dentin irradiated with femtosecond pulsed laser

Rq between G4 and G6 was disclosed ($P<0.001$) and the Tamhane's T2 test revealed a significant difference of Rz between G4 and G6 ($P<0.001$). A Wilcoxon test was also performed with roughness parameters among different scanning speed and showed a significant difference of each roughness parameter ($P<0.001$).When v=2400 mm/s and d=24 µm, each surface roughness parameter was always higher than when v=1200 mm/sand d=12 µm was used.

Compared to the roughness results of mechanical prepared samples, roughness parameters obtained with TF-12 bur lied upon all the laser ablated samples, and roughness parameters prepared with diamond bur FO-20EF valued between laser ablated samples when v=2400 mm/s, d=24µm and v=1200 mm/s, d=12µm.

Scanning electron microscopy

The micromorphology of dentin after femtosecond pulsed laser was studied. Dentin surfaces with open dentinal tubules were observed (Figure 2). The SEM images of G1, G2 and G3 showed more rough surface morphology with obvious ridges and valleys. Samples from G4, G5 and G6 had more flat surfaces. At some areas, the dentin melted and fused into a sheet with adjacent tissues, the original structure of dentin disappeared, and this phenomenon can be observed in almost all dentin samples. With increasing laser fluence and decreasing scanning speed, the debris-like structure seemed to increase and

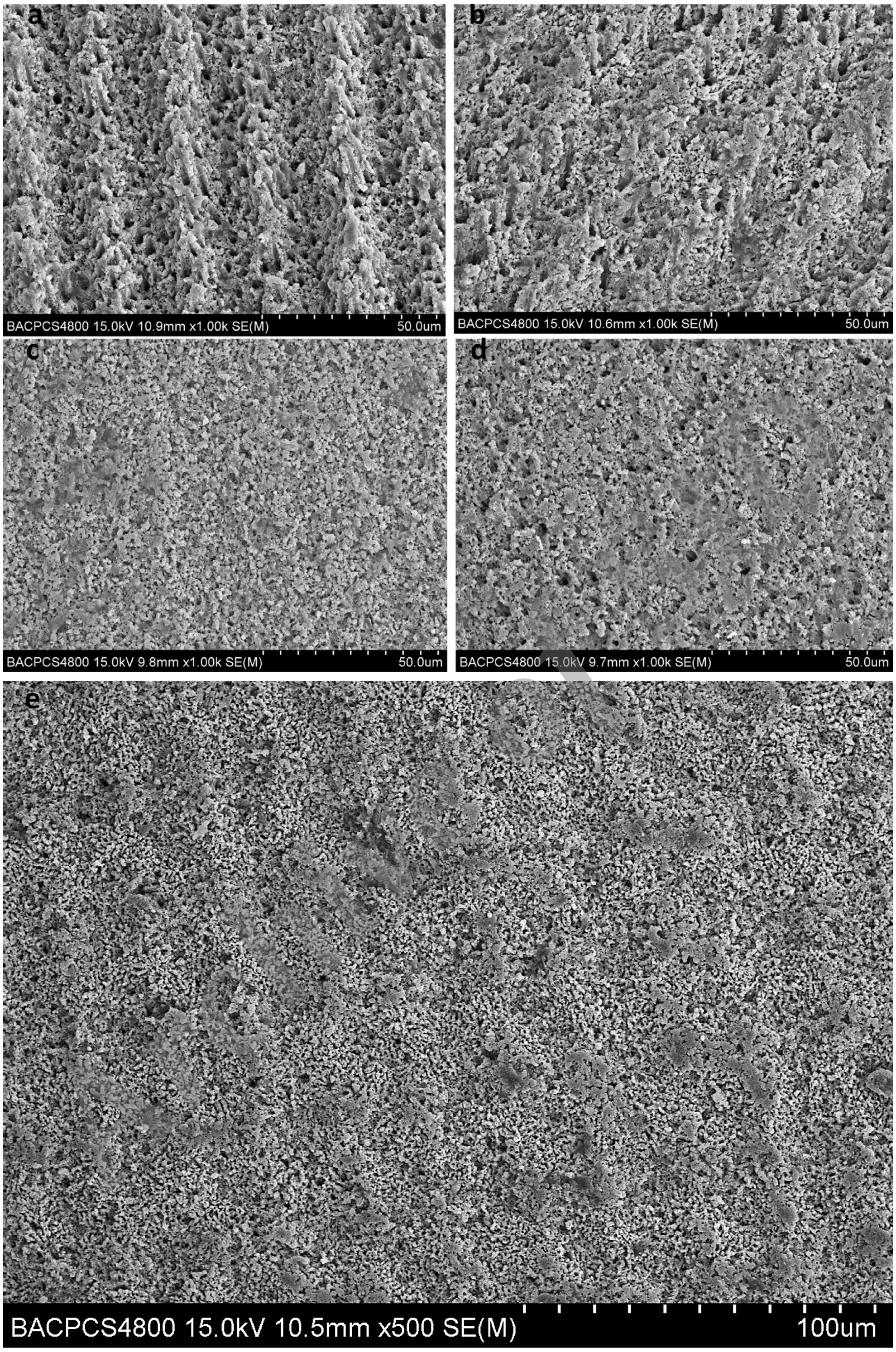

Figure 2. SEM micrograph of dentin after femtosecond laser with: a F=2 J/cm^2, v=2400 mm/s,d=24μm (SEM × 1000); b F= 4 J/cm^2, v=2400 mm/s, d=24μm (SEM × 1000); c F=2 J/cm^2, v=1200 mm/s, d=12μm (SEM × 1000); d F= 4 J/cm^2, v=1200 mm/s, d=12μm (SEM × 1000); e F= 8 J/cm^2, v=2400 mm/s, d=24μm (SEM × 500).

occlude part of dentinal tubules. It is noted that, samples from G3 showed a characteristic morphology, the debris-like structure was distributed regularly on ridges, the distance between two areas of debris-like structure were about the same as spot size, and each area of debris-like structure almost lied on the same position of each ridge.

Discussion

The mechanism of femtosecond laser on dental hard tissues is plasma-mediated ablation. The atoms and molecules on the irradiated material surface are ionized to form plasmas, little heat is generated, and the collateral damage is minimized [18, 24-28].

In this study, a femtosecond pulsed laser with different parameters was used for the ablation of dentin. The surface roughness of irradiated dentin samples were studied quantitatively and morphology was observed with SEM. The melting and resolidification of dentin after ablation with femtosecond pulsed laser is not consistent with most previous reports in literatures[29, 30]. Rego F FA et al. reported that thermal damage can be present when higher laser power is used or dehydration level of tooth is high [31]. The melting and resolidification of debris-like structure seemed more common in this study, especially with increasing laser fluence and decreasing scanning speed. The characteristic surface morphology of G3 might indicate that there was a regular heat accumulation during the ablation process, while it was not that obvious when a lower fluence was used. In the previous study of our research group, the morphology of melting and resolidification of dental hard tissues was observed with the ablation of a low repetition rate and high fluence femtosecond pulsed laser [32]. The exact mechanism of this phenomenon still needs further research.

The surface of dentin prepared with mechanical instruments is smooth, and with the presence of a smear layer and occluded dentinal tubules, it must subsequently be upgraded to provide anchorage for restorative materials [3, 20]. After ablation of femtosecond pulsed laser, most of the dentinal tubules were opened, which will definitely increase the effect of mechanical interlocking of luting cements in the retention of restorative materials, which may lead to render the acid etching not necessary. It will simplify the clinical operation procedure and reduce damage to the teeth. With adequate parameters of femtosecond pulsed laser, a number of opened dentinal tubules can be obtained, which will further increase the effect of mechanical interlocking.

Surface roughness is one of the most important factors that influence and evaluate the quality of a tooth preparation, and the surface roughness of the axial walls could relate to the precision of a cast and contribute to the retention of a cast restoration [33]. In this study, scanning speed and scanning distance determined the overlap of pulses within and between scanning lines. The SEM images revealed that the dentin surface was always flat within a scanning line despite the different scanning distance used, while the surface roughness of dentin ablated with different parameters differed from each other. With this information, it can be inferred that the holistic flatness of a laser ablated dentin sample is predominated by the scanning distance rather than scanning speed in this experiment. When compared to the roughness of a mechanical prepared dentin sample, the G1, G2, G3 lied between the two kinds of diamonds burs, while the G4, G5, G6 were almost the same or slightly lower than the FO-20EF prepared dentin sample. An EF bur has a fine-grit, which is often used to finish a tooth preparation. Without finishing, the excessive roughness and rugged axial-wall could lead to the sharp peaks formation of a casting which may become reduced with the successive steps of impression, die, wax pattern, investment, and casting, therefore, since undersized castings are produced [33], the placement of a prosthesis become difficult [34].

The surface roughness also has an effect on the wettability of dentin. Surface irregularities promote wettability by producing increased surface area. The bond between the adherent surface and the adhesive will be subsequently stronger, meaning that, extremely smooth surface of a tooth preparation may lead to adhesive clinical failure with traditional, non-adhesive cements[33, 35]. In this study, femtosecond pulsed laser with different parameters resulted in diverse surface topography of dentin, doctors should choose adequate parameters setting to achieve therapeutic benefit by considering characteristics and treatment plan of each patient.

Conclusion

Better morphology of dentin can be achieved by ablation with femtosecond pulsed laser. Selection of fluence, scanning speed and scanning distance of a femtosecond pulsed laser caused great impact on the surface characteristics of dentin. Higher fluence, lower scanning speed and scanning distance lead to a smooth surface and vice versa. Adequate parameters should be chosen to ensure an effective therapy.

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