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Full Length Research Paper

The ablation threshold of Er:YAG laser and Er,Cr:YSGG laser in dental dentin

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This study aims to investigate the threshold dose for the ablation of dentin of human permanent tooth using erbium: yttrium-aluminium-garnet (Er:YAG, wavelength 2.94 µm, pulse duration 100 µs-50 ms) and erbium, chromium: yattrium-scandium-gallium-garnet (Er,Cr:YSGG, wavelength 2.79 µm; pulse duration 140 µs) lasers. A total of 70 dentin samples were subject to the experiment with varying laser energy densities ranging from 0 - 10 J/cm2. The treated dentin surfaces were examined through stereomicroscope and scanning electron microscope. The result of the experiment indicated that both Er:YAG and Er,Cr:YSGG lasers are effective in ablating human tooth dentin. The ablation thresholds for both lasers were determined by inspecting the scanning electron microscopy (SEM) micrographs. The ablation threshold value for Er:YAG laser in dental dentin is 2.97–3.56 J/cm2, and for Er,Cr:YSGG laser, it is 2.69 - 3.66 J/cm^2.

Key words: Dentin, Er:YAG laser, Er,Cr:YSGG laser, ablation, ablation threshold.

INTRODUCTION

Caries removal and cavity preparation for restorations using mechanical means are often accompanied by fear and pain for the patient. Meanwhile, the use of laser for such procedures causes no pain and vibration, which is one of the factors that stimulated dentists' early interest in lasers (Featherstone et al., 1998; Powell et al., 1992; Wigdor et al., 1995; Schwarz et al., 2002). Hibst and Keller (Hibst and Keller, 1989) first introduced the Er:YAG laser for cutting dental hard tissue. In their studies, they concluded that the laser would cause no damage (fuse/carbonization/pulp degeneration) to the hard tissue and dental pulp under proper water cooling conditions. In October 1998, the US Food and Drug Administration (FDA) have approved the Er,Cr:YSGG laser for dental application owing to its good performance in preparing the dental cavity. Yet, the exact mechanism of the ablation of tooth hard tissue with Er:YAG laser and Er,Cr:YSGG laser is still not clear.

There are several different theories, but none of them has yet been established. Mir M et al. (2009) provided a new concept of monitoring of direct interactions between laser light, water and enamel, which is different from that of concepts and methods of exploring the mechanisms based on heat formation, transformation and mathematical calculations evaluating the outcome of ablation. In the end, they concluded the mechanism of laser cutting under water after observation of the clips and images from the high-tech camera in four steps. As to the ablation threshold and morphological changes of the enamel after laser treatment, several studies were carried out by Shi and Apel, respectively (Shi et al., 2009; Apel et al., 2002).

Both Er:YAG and Er,Cr:YSGG lasers are effective in preparing tooth cavities. They result in minimal side-effects on the sound tooth tissue (Reza et al., 2007; Feuerstein et al., 1992; Serebro et al., 1987). Besides the enamel, dentin is the other major component of the teeth. Dentin is rich in organics, and there are numerous odontoblast processes and dentinal tubes radiating from the pulp chamber to the enamel-dentin border. The tubes are filled with liquids; external stimulation can make these

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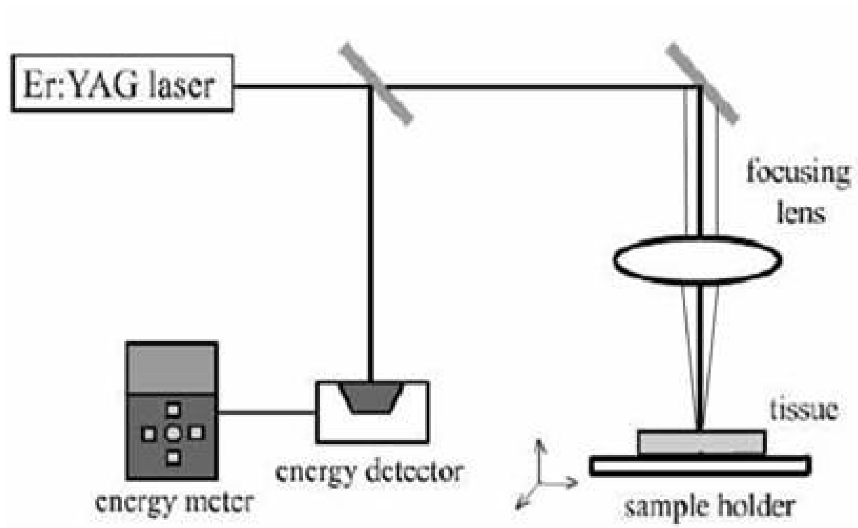


Figure 1. Schematic illustration of the experiment set-up of the Er:YAG laser.

liquids flow, and the changes are transmitted to the pulp nerves. Patients are much more sensitive about the cutting of the dentin than that of the enamel. In order to reach a better understanding of the two Erbium lasers, the present experiment was carried out by investigating the ablating threshold of Erbium lasers in human dentin.

MATERIALS AND METHODS

Sample preparation

30 extracted human permanent molar teeth, which are free of caries, restorations, cracks, or obvious defects, were cleaned and stored in 0.9% physiological saline solution (NaCl) for a maximum of one month following extraction.

For our study, the teeth were sectioned into two to three segments in the axial direction using a low-speed diamond saw (650: SBT, USA), according to the previous study (Apel et al., 2002). Each section was abraded to remove the enamel and expose the superficial dentin surface, and the samples were prepared with 180-grit SiO_2 papers.

A total of 70 samples were obtained after the above-mentioned procedures were done. The samples were randomly divided into two groups: one treated with Er:YAG laser and the other with Er,Cr:YSGG laser. The Er:YAG laser (Contour Profile 2940, USA) experimental set-up is shown in Figure 1. The lasing medium of the Er:YAG laser emitted laser light of 2.94 μm and pulse duration is in the region of 100 μs-50 ms. Its repetition rate was set at 1 Hz and irradiation time at 1 s, so, the pulse number irradiated at each site was 1. The spot size was about 1 mm, which was measured by examining the burn patterns on the exposed Polaroid film placed at the plane of the tissue sample.

The Er,Cr:YSGG laser (WaterlaseTM, BioLaser Technology, USA) experimental set-up is shown in Figure 2. This system emitted light with a wavelength of 2.79 μm and a pulse duration of 140 μs. The repetition rate was 20 Hz, and the irradiation time was about 5 s; thus, the pulse number irradiated at each site was 100. The air pressure and water level was set at 60 -70%, respectively, according to the manufacturer's instructions. Laser energy through a fiber optic system was delivered to a sapphire tip terminal with a diameter of 600 μm and a length of 6 mm. The spot size was about 750 μm and the distance between the tip and the tissue samples was 1 mm, which was measured by a homemade set with a graduated scale.

Each tooth sample was irradiated with increasing energy densities of 0 -10 J/cm^2 for both Er:YAG and Er,Cr:YSGG lasers. An energy meter (PE50BB, Ophir, Israel) was used in the study to measure the energy output, and then the energy densities were calculated as the ratio of the energy to the spot area.

Evaluation standards and detailed observations

Notes were made about the visual observations done during and after laser irradiation, such as the discoloration of the hard tooth tissue, sparking, or smoke evolution. After irradiation, we used a stereomicroscope (mz16fa, Leica, Germany) to examine the samples for signs of ablation. Two calibrated and experienced examiners assessed the photographs, looking for the patterns mentioned above. Only the removal of hard tissues can be defined as laser ablation; discoloration could not be treated as such.

A detailed observation of the irradiated areas was then performed using scanning electron microscope (JSM: 6380lv, JEOL, Japan) images.

Statistical analysis

The results were analyzed statistically by calculating the probability of the occurrence of ablation for the Er:YAG and Er:YSGG lasers using Probit multiple regression analysis. We define a sensitivity of 80% in the statistical analysis. Figure 3 shows the probability of the occurrence of ablation as a function of energy density.

RESULTS

Threshold determination

Based on observations under a stereomicroscope and on

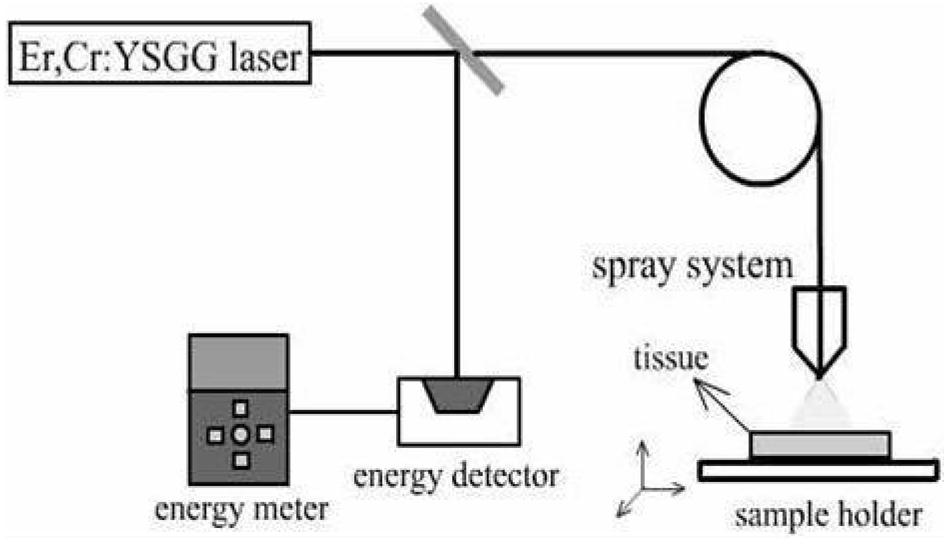


Figure 2. Schematic illustration of the experiment set-up of the Er,Cr:YSGG laser.

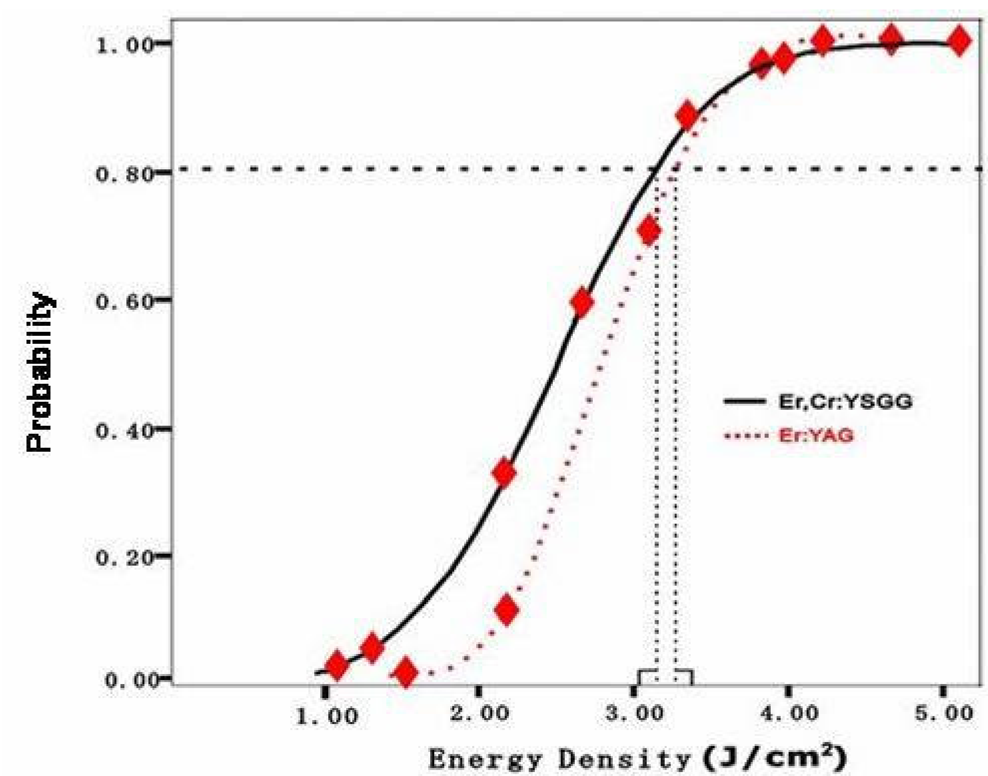


Figure 3. Probability of the occurrence of ablation as a function of the energy density of laser ablation dentin.

images obtained with a scanning electron microscope (Figures 4 and 5), we defined the energy density ranges as the ablation thresholds for the Er:YAG and Er,Cr: YSGG lasers. With the Er:YAG laser, the transition was found to lay in the range of energy densities of between 2.97 and 3.56 J/cm^2. In a few exceptional cases, however, ablation already occurred below this threshold, or conversely, no ablation was seen above this threshold. The range for the Er,Cr:YSGG laser was slightly lower at 2.69 - 3.66 J/cm^2. Again, there were some “mavericks”

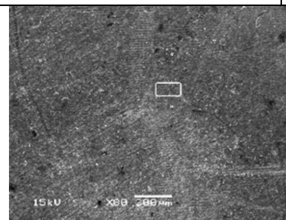
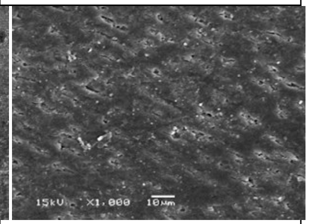
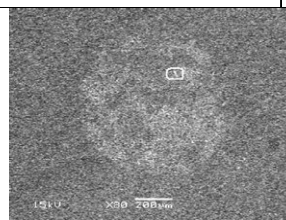
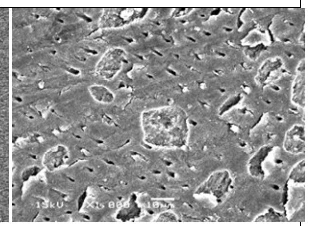
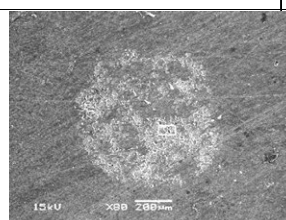
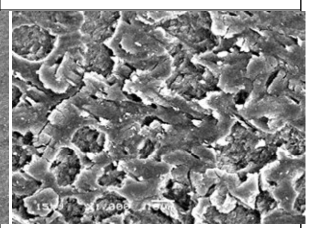
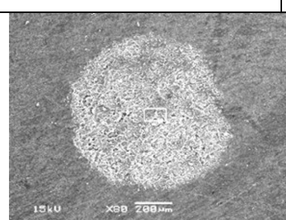
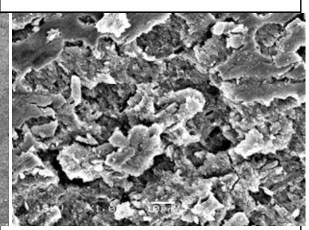
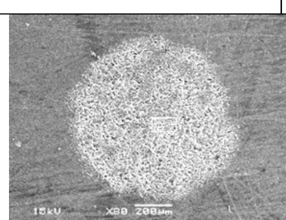
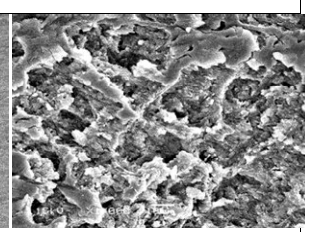
Energy density	Magnification (80 X)	Magnification (1,000 X)
1.43 J/cm^2 (no ablation was seen)		
2.20 J/cm^2 (ablation occurred partially in the irradiated area)		
3.09 J/cm^2 (remarkable ablation in the dental dentin)		
3.86 J/cm^2 (much more clear ablation was seen)		
4.78 J/cm^2 (remarkable ablation over the irradiated area)		

Figure 4. Sample SEM images for the Er:YAG laser ablation of dentin.

some "mavericks" below and above this range.

SEM images

Using a scanning electron microscope, we observed the irradiated areas in details. It showed that both Er:YAG and Er,Cr:YSGG lasers produced crater-form changes with irregular borderlines on the irradiated dentin surfaces. In the images with a magnification of ×1,000, we could see that the dentinal tubules were open and that there was partial fusion at the irradiated area (Figures 6 and 7). In some cases, the SEM images show micro-fragments and microcracks on the surfaces after irradiation. A slight faint, white, or brownish discoloration within the dental dentin was also observed in some cases during the irradiation of the samples with both lasers. The occurrence of these effects was irregular and could not be assigned to any particular energy density.

DISCUSSION

Enamel caries is the beginning of most tooth decay, which causes less adverse effects to the daily life of patients, and rarely arouses patients' awareness of dental treatment. In dental clinical practices, dentin caries is more common than enamel caries; in a certain sense,

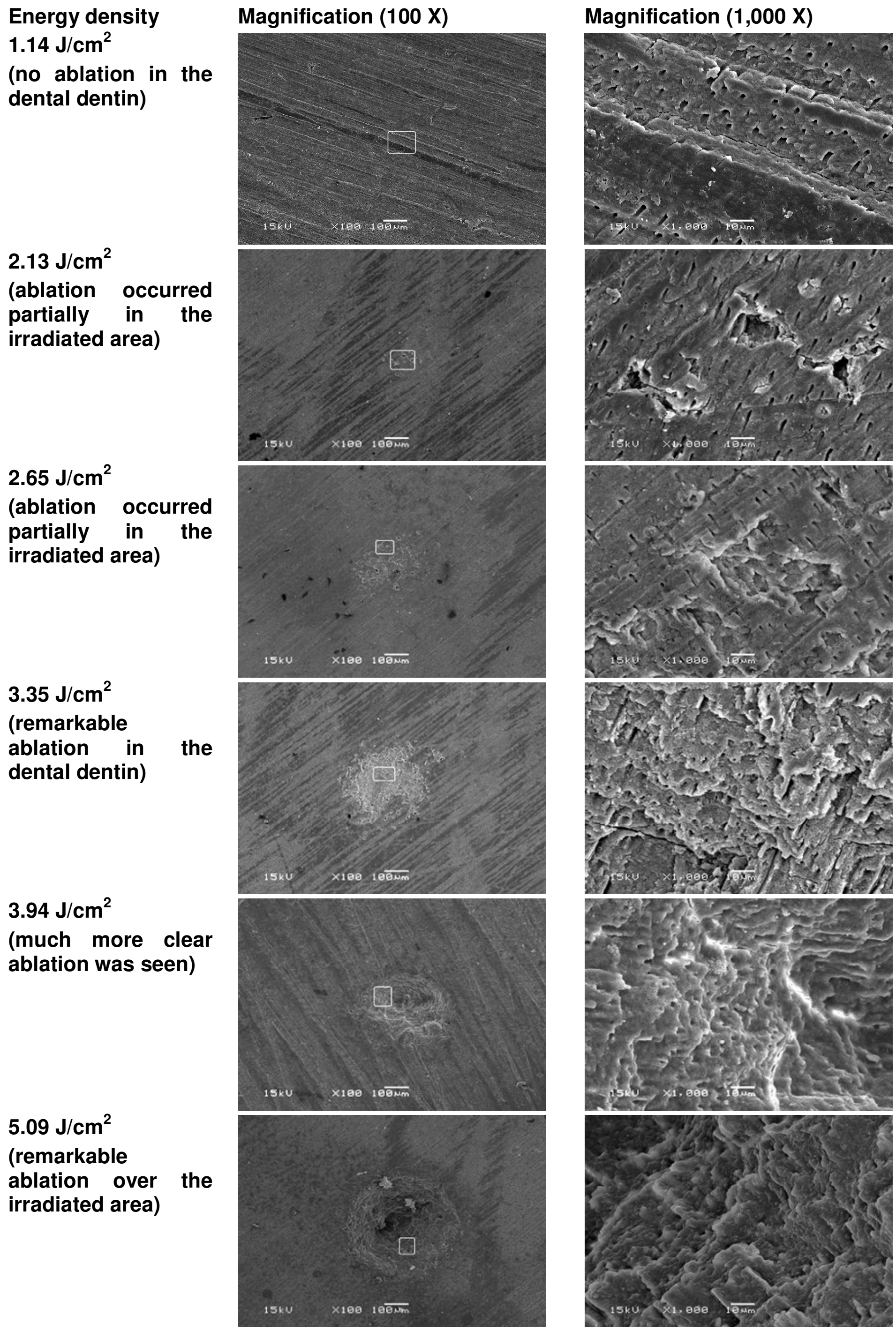


Figure 5. Sample SEM images for the Er,Cr:YSGG laser ablation dentin.

and Er,Cr:YSGG lasers to the dentin have been studied in order to obtain information on the use of lasers in clinical practices.

The ablation capability of lasers is closely related to the composite nature of the dentin. Dentin can be classified as a biological composite containing volume, approximately 20% water, 47% mineral, and 33% protein and lipid. Correspondingly, there are three primary absorbing bands for dentin: at around 3 μm, around 7 μm, and between 9 - 11 μm (Featherstone et al., 2001). The absorption at 3 μm is related primarily to water in the tissue and there is also a spike at about 2.8 μm which is related to the OH- ion in the hydroxyapatite mineral. The band at around 7 μm is where the carbonate ion that the

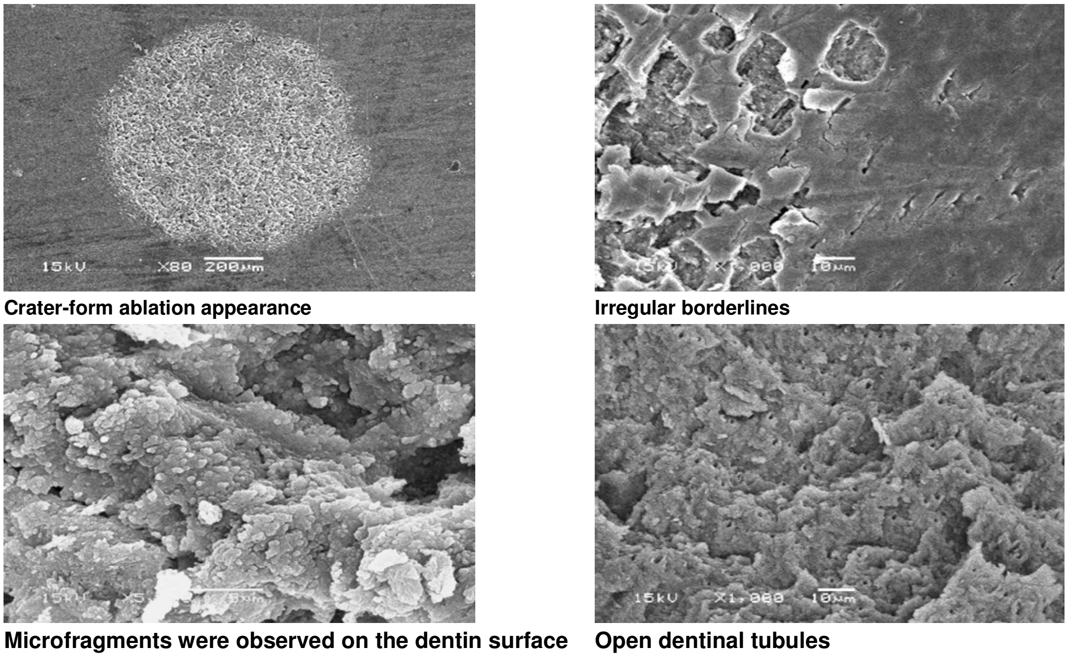


Figure 6. Sample SEM images for the Er:YAG laser of dentin.

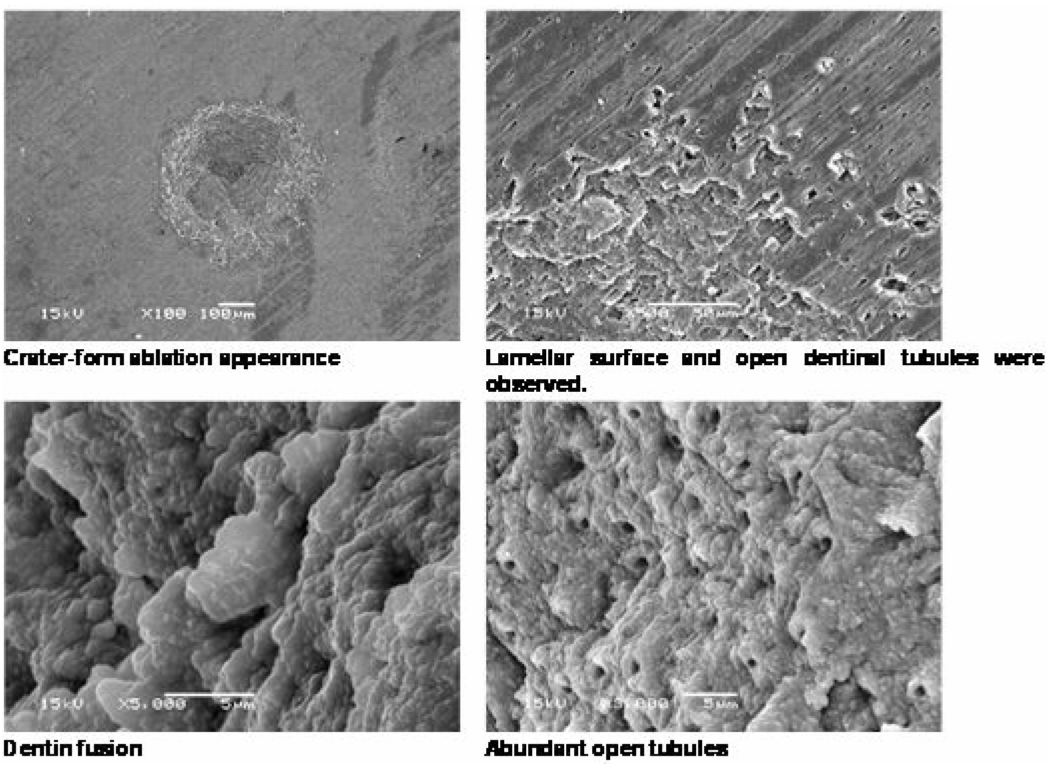


Figure 7. Sample SEM images for the Er,Cr:YSGG laser ablation dentine laser ablation dentin.

preparation of dental cavity is the process of cutting the dentin. In this research, the effects of both Er:YAG substitutes phosphate in dental mineral absorbs light and is also the absorbing peak of the protein. In the region of 9 - 11 μm, the primary absorber is phosphate ion. The carbonate ion and water also absorb in the same region.

The Er:YAG laser emission (wavelength of 2.94 µm) is coincident to the main absorption band of water and is also well absorbed by the OH- groups in hydroxyapatite mineral. During irradiation, the incident energy is absorbed by water molecules and OH- groups in the dentin crystalline structures, thus, causing a higher and quicker vaporization of the water; the quick expansion, followed by microexplosions produces the ejection of both organic and inorganic tissue particles below the melting point (approximately 1,200) of tooth tissue (Lukac et al., 2004; Meister et al., 2006; Serebo et al., 1987; Delfino et al., 2006), which constitute the major principle of Er:YAG laser ablation (Apel et al., 2002; Corona et al., 2007; Ekworapoj et al., 2007). The laser ablation produces carbonization, fusion, recrystalization, bubble incisions, and microcracks, among others (Frentzen et al., 1992; Malmstrom et al., 2001; Aminzadeh et al., 1999; Corona et al., 2003; Hibst et al., 1989).

In a previous study (Shi Lin et al., 2009), the thresholds of Er:YAG and Er,Cr:YSGG lasers in enamel were found to be 3.19 - 4.36 J/cm2 and 4.12 - 4.80 J/cm^2, respectively, which are higher than those of dentin. This may be attributed to the following reasons: Enamel is composed by volume of 85% mineral (predominately carbonated hydroxyapatite), 12% water, and 3% organic proteins. Majority of free water exists within the peri-prismatic protein matrix. Dentin has a higher water content and less mineral density than enamel; it is composed by volume of 47% mineral (carbonated hydroxyapatite), 33% protein (mostly collagen), and 20% water. Consequently, the ablation rate for dentin is faster than that for enamel, and the power parameters can be correspondingly lower. Moreover, tooth dentin has abundant dentinal tubules, which make it as porous as sponge. In addition, the tubules provide the tissue with elasticity and relatively low hardness, which would then result in the dentin's lower ablation threshold with these lasers.

At present, there are very little data about the action mechanism of Er:YAG lasers on human dentin, which can be retrieved. In their papers, Hibst and Keller, 1989 stated that the ablation threshold for the Er:YAG laser is approximately 10 J/cm^2. Meanwhile, Farrar et al. (1997) calculated the ablation threshold at 5.2 J/cm^2. For the threshold of the Er,Cr:YSGG laser on human dentin, there is no literature that can be obtained. In our study, 70 dentin samples were prepared and randomly divided into two groups, then treated with Er:YAG and Er,Cr:YSGG lasers with increasing incident energy densities of 0 - 10 J/cm^2. The surface changes were assessed by a stereomicroscope and a scanning electron microscope in order to identify the energy density range as the ablation threshold for both Er:YAG and the Er:YSGG lasers. The ablation threshold value of the Er:YAG laser in dental dentin is 2.97–3.56 J/cm2, while that of the Er,Cr:YSGG laser is 2.69–3.66 J/cm^2.

The Er,Cr:YSGG laser (wavelength of 2.79 µm) is another kind of laser that has been widely studied after the Er:YAG laser. Eversole and Rizoiu, 1995; Eversole et al., 1997; Eversole et al., 1995, indicated separately in their studies that the Er,Cr:YSGG laser is safe to use in cutting dental hard tissue. The principles of Er,Cr:YSGG laser ablation consists of two aspects: absorption of incident energy by the ablated dentin and the resulting microexplosion. The other mechanism of the Er,Cr:YSGG laser is called the laser-powered hydrokinetic system, where in the incident energy is first absorbed by water molecules and then sent to the dentin surface. In this study, the Er,Cr:YSGG laser was initially introduced in cutting human tooth dentin. The result indicated that the ablation threshold of the Er,Cr:YSGG laser in human dentin is 2.69 - 3.66 J/cm^2, which enriches our understanding of this new kind of laser.

It is obvious that, at constant radiant exposures (corresponds to the energy density), changes in the light-material interaction will occur if the duration of the exposure to the laser is reduced. Thus, the interactions occurring at a constant radiant exposure can range from biostimulation to photodisruption (Katzir, 1993; Apel et al., 2002) described the influences of the pulse duration of an Er:YAG laser system on the ablation threshold of enamel; In the end, the results revealed that both the pulse duration and the radiant exposure have a statistically significant influence on the ablation threshold (logistic regression, $p < 0.0001$). However, the threshold shift is so slight that no clinical consequences can be expected. Majaron et al. 1996 firstly examined the ablation threshold in dentin and concluded that a change in the pulse duration in the range of 50 µs to 1 ms has no effect on the ablation threshold of dentine. Against this backdrop, further studies should be carried out to demonstrate the dependence of the ablation threshold of dental dentin on the pulse duration.

The effect of preparation with lasers on the intrapulpal temperature is probably the biggest problem in using the lasers for preparation of dental hard tissue. Geraldo Martins et al. 2005 concluded in their study that the use of the Er:YAG laser promoted acceptable temperature increases inside the pulp chamber. Burkes et al.1992 reported that when Er:YAG laser was irradiated without water spray, intrapulpal temperature rose more than 27°C, which is greater than that considered safe for pulp survival. Eversole et al. 1995 reported that no pulpal inflammatory responses could be identified in Er,Cr:YSGG laser irradiated with a water spray. In the present study, carbonization and fusion were observed in the superficial layer of ablated dentin at the threshold range of both lasers, while the temperature increase using the same parameters should be further studied.

Conclusions

The transition for the Er:YAG laser is found at an energy density range of 2.97 - 3.55 J/cm^2. That for the Er,Cr:YSGG laser is slightly higher at 2.69 - 3.66 J/cm^2. The gross and microappearance of the lased surface is essentially in crater form, which is markedly different from the classical surface morphologies obtained with traditional rotary instrumentation. In addition, the microdislocation of mineral at the crater edges, visually evident as “etched” in appearance, can be beneficially employed in aiding the bonding of composite resin materials.

Finally, the open dentinal tubules would have a potential effect on the following bonding procedures, which need further studies for a better understanding on the mechanism involved.

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