Determination of ablation threshold of dental hard tissues irradiated with Er:YAG and Er,Cr:YSGG lasers

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We evaluate the ablation thresholds of Er:YAG and Er,Cr:YSGG laser for enamel and dentin. A total of 140 dental slices is evenly divided into two groups: the dentin group and the enamel group. Dental tissues are irradiated with either an Er:YAG laser or an Er,Cr:YSGG laser with pulse widths in the order of 100 μs. The laser fluence is increased gradually until the ablation crater is formed. The laser ablation threshold is calculated using probit analysis. The ablation thresholds of the Er:YAG laser for dentin and enamel range from 2.88 to 3.36 J/cm^2 and from 2.94 to 3.8 J/cm^2, respectively, and the ablation thresholds of the Er,Cr:YSGG laser for dentin and enamel range from 2.92 to 4.2 J/cm^2 and from 4.93 to 5.66 J/cm^2, respectively.

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Er lasers are considered the most promising alternatives to traditional mechanical instruments for the preparation of various tooth structures[1,2]. The primary ablation mechanism of Er-based lasers is the thermomechanical process. Laser energy absorbed by water can heat interstitial water and raise internal pressures to reach the ultimate tensile strength of hard tissue. These phenomena result in the removal of the outer layers of dental tissues without thermal and mechanical damage to the surrounding tissues or tooth pulp[3−5]. The application of laser ablation in dentistry has attracted increasing attention because of its unique advantages, such as noncontact modality, reduced pain, and accurate removal of damaged tissue.

Selecting appropriate laser parameters suitable for a given dental condition is important. One of the fundamental issues in laser ablation is the determination of the ablation threshold of different laser wavelengths in dental hard tissues. For example, when removal of caries, enamel, or dentin is desired, the laser energy must be higher than the ablation threshold. However, for caries prevention, chemical or structural changes, rather than ablation, are desired, and the laser energy must be lower than the ablation threshold. Knowledge of the ablation thresholds of dental hard tissues constitutes the basis for laser use in dentistry.

Several studies have attempted to evaluate the ablation thresholds of Er lasers since they are first introduced to the medical field in the late 1980s. In 1989, an early investigation demonstrated that Er:YAG lasers were capable of effectively ablating dentin and enamel tissues[6]. In addition, the ablation threshold values of dentin and enamel were calculated based on a simple model. A preliminary comparative study of the 3-μm laser actions of Er-doped YAG, YSGG, YAP, and YLF lasers on dental hard tissues has also been performed[7]. Apel *et al.*[8] found that the ablation threshold of Er:YAG lasers could be influenced by the pulse duration and radiant exposure. In this study, a shift to lower radiant exposure at the lower limit for the onset of ablation is observed when the pulse duration is shorter.

Several methods, for instance, probability statistics of the occurrence of ablation[9,10], theoretical calculations[6], the optoacoustic measurement approach[11,12], and curve fitting[13−15] in which the intersection of the extrapolated ablation rate curve and horizontal axis is taken as the threshold, have been adopted to determine the ablation threshold. However, a global ablation model has yet to be established because of the complex nature of the interactions between lasers and dental hard tissues. Moreover, considering the diverse characteristics of biological tissues, the determination of ablation thresholds is difficult because it can be affected by a number of factors. To date, probability statistics is believed to yield threshold values closest to the actual value[9].

This letter evaluates the ablation thresholds of Er:YAG and Er,Cr:YSGG lasers for dental enamel and dentin.

53 second molars with completed root growth were collected from 46 healthy subjects (18–30 years old, 34 males, 12 females). The molars were removed by extraction or osteotomy for medical reasons. The use of human molars in this letter was approved by the Ethics Committee of Fujian Normal University. The remaining soft tissue on the extracted teeth was removed and the teeth were thoroughly rinsed in tap water. The teeth were cut into 2 or 3 slices ($\sim$ 1 mm thickness) along the longitudinal direction using a diamond wheel saw (Model 650, South Bay Technology Inc., USA). A total of 140 slices was obtained and stored in physiological saline at 4 °C before use. The treated parts focused on the occlusal and central region of the slices near the center of the tooth. The exposed surface of the hard tissue slice was ground by a water-cooled polishing machine using a series of silicon carbide sandpapers of 240–1200 grit followed by ultrasonic cleaning. Dental samples were evenly and randomly divided into enamel and dentin groups and each group was evenly and randomly divided into two irradiation groups: the Er:YAG group and the Er,Cr:YSGG group. The irradiated area focused on the

middle enamel and dentin.

Er:YAG laser beams (Contour Profile 2940, Sciton, USA) were transmitted through an articulated-mirror-arm system and focused on the sample surface through a lens. The radiant exposure delivered to the dental sample was monitored by an energy meter (NOVA II, Orphir, Israel) coupled to a pyroelectric detector (Fig. 1(a)). Er,Cr:YSGG laser beams (Waterlase^{TM}, BioLase Technology, USA) were transmitted through an optic fiber system to a handpiece consisting of a sapphire tip (Fig. 1(b)). Laser energy was measured before and after each experiment. When the measured energy had decreased by over 15% of the initial energy during the experiment, the tip was replaced. In addition, a built-in pressurized water spray system with adjustable flow rate was incorporated into the handpiece. Based on pre-experimental results, the air pressure and water level were set to 60% and 70%, respectively. The laser irradiation parameters are listed in Table 1. Laser fluence was gradually increased until an ablation crater was generated.

After laser irradiation, tooth samples were examined and imaged under a stereomicroscope (MZ16FA, LEICA, Germany). Detailed structural changes in the irradiated areas were further examined by a scanning electron microscope (SEM, JSM-6380LV, JEOL, Japan). The images were then examined by a dentist and a physicist to determine the occurrence of ablation. The appearance of a crater or the removal of hard tissue was used as a criterion of laser ablation. The ablation was scored as 1 (tissue removal) or 0 (no tissue removal)[9].

The probability of the occurrence of ablation for different tissue types and lasers was calculated by probit analysis[9]. The threshold irradiation exposure was determined as the laser dose under which ablation occured in 80% of the specimens. The 95% confidence interval of the threshold irradiation exposure was defined as the threshold range.

Although the superficial layer of the dental samples can be ablated by Er:YAG and Er,Cr:YSGG lasers once a certain laser energy is achieved, more dentin tissue is removed compared with enamel tissue under the same laser fluence (Fig. 2). As expected, ablation occurs more markedly at the center of the beam compared with the edge of the crater at the microscopic level and results in a corrugated profile (Fig. 3). Dentin samples exhibit several open dentinal tubules with remaining debris after Er:YAG laser irradiation (Fig. 3(a)). By contrast, the dentin surface is cleaner after Er,Cr:YSGG laser irradiation and more open dentinal tubules and less debris are observed (Fig. 3(c)).

Whether or not and to what extent the ablation of dental hard tissue occurs were quantitatively determined based on stereomicroscope examinations and SEM. An ablation threshold is observed for both dentin and enamel tissue. Below this threshold, no tissue removal is discernable, as demonstrated by the laser fluence escalation experiment. Figure 4 shows the probability of the occurrence of ablation in the enamel and dentin tissue as a function of the energy density of the Er:YAG and Er,Cr:YSGG lasers. Probit analysis indicates that the thresholds of the Er:YAG laser for dentin and enamel are 3.08 and 3.27 J/cm^2, respectively (Figs. 4(a) and (b)).

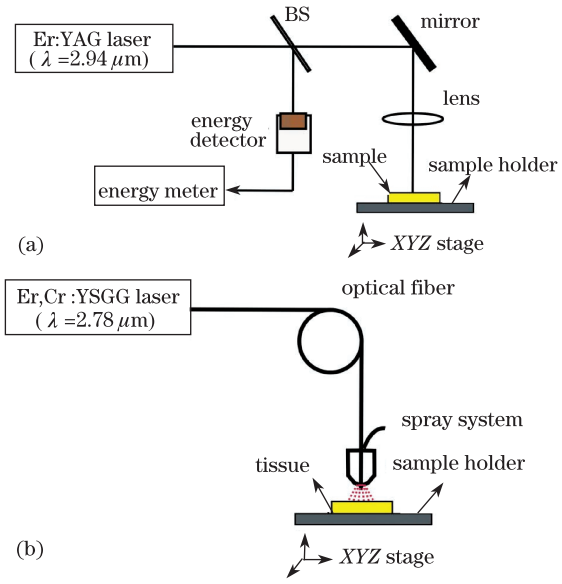

Fig. 1. Illustration of the experimental setup. (a) Er:YAG laser and (b) Er,Cr:YSGG laser.

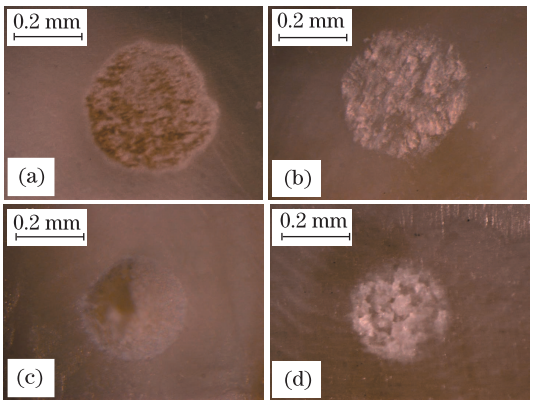

Fig. 2. Tissue ablation by different lasers as observed under a stereomicroscope. (a) Dentin and (b) enamel tissues irradiated by the Er:YAG laser at 3.86 J/cm^2. (c) Dentin and (d) enamel tissues irradiated by the Er,Cr:YSGG laser at 5.09 J/cm^2.

Table 1. Parameters of Laser Irradiation

Lasers	Pulse Width (μs)	Spot Size (mm)	Pulse Rate (Hz)	Work Distance (mm)	Time (s)	Energy Density (J/cm^2)	
						Enamel	Dentin
Er:YAG	$\sim$ 200	1	1	25	1	1.43–4.78	1.43–4.78
Er,Cr:YSGG	140	0.74	20	1	5	1.14–5.82	1.14–5.09
	140	0.89	20	1	5	0.93–4.83	0.93–3.94

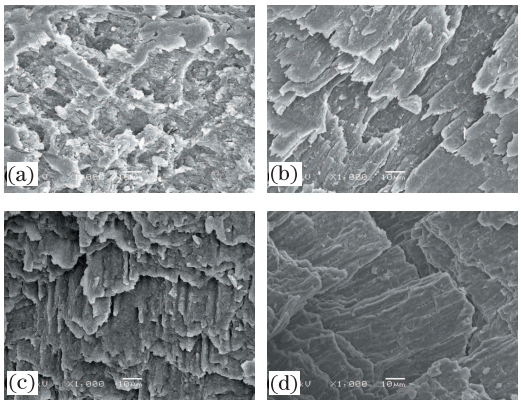

Fig. 3. Tissue ablation by different lasers as observed under SEM. (a) Dentin and (b) enamel tissues irradiated by the Er:YAG laser at 3.86 J/cm^2. (c) Dentin and (d) enamel tissues irradiated by the Er,Cr:YSGG laser at 5.09 J/cm^2.

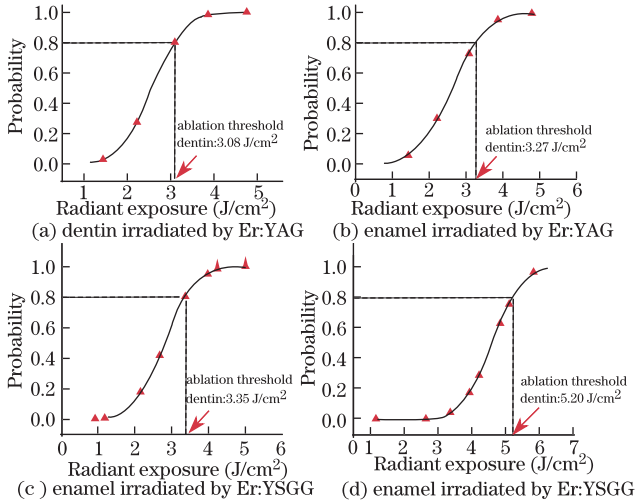

Fig. 4. Probability of the occurrence of dental tissue ablation by Er:YAG and Er,Cr:YSGG lasers.

The thresholds of the Er,Cr:YSGG laser for dentin and enamel are 3.35 and 5.20 J/cm^2, respectively (Figs. 4(c) and (d)).

The ablation threshold ranges of the Er:YAG and Er,Cr:YSGG lasers for enamel and dentin are shown in Fig. 5. The ablation thresholds of the Er:YAG laser for dentin and enamel range from 2.88 to 3.36 J/cm^2 and from 2.94 to 3.8 J/cm^2, respectively. The ablation thresholds of the Er,Cr:YSGG laser for dentin and enamel range from 2.92 to 4.2 J/cm^2 and from 4.93 to 5.66 J/cm^2 for dentin and enamel, respectively.

A crucial issue in laser applications in dentistry is the evaluation of ablation thresholds using different laser wavelengths. In this letter, the Er:YAG and Er,Cr:YSGG laser thresholds for enamel and dentin were systematically evaluated. Table 2 summarizes the ablation thresholds of dental hard tissues published in different reports. Regardless of the type of tissue used, dentin or enamel, the threshold values for the Er:YAG laser obtained in this letter are slightly lower than those in previous studies[6,7,10,14,16]. The ablation threshold of enamel for the Er,Cr:YSGG laser is 5.20 J/cm^2, higher than those in Refs. [7,9] (4 and 2.1 J/cm^2, respectively) but much lower than that in Ref. [10] (13 J/cm^2).

Based on a comparison between the ablation thresholds established by each research group, a noticeable discrepancy may be observed. This discrepancy may be attributed to several factors. Firstly, tissue characteristics, including optical, thermodynamic, and mechanical properties, vary among different types of tissues. The dental samples used among published studies vary. For instance, Apel *et al.*[10] used wisdom teeth as targets whereas Kang *et al.*[9] used adult human molars. Even when the same type of dental tissue is used, the composition of dental tissues may show regional differences, and these difference can affect the ablation threshold. The difference in laser ablation was validated with the cervical and buccal or oral regions of the enamel[10]. Secondly, Ablation thresholds may further be affected by various laser parameters, such as the wavelength, repetition rate, and pulse duration. For example, the pulse width of the Er,Cr:YSGG laser used in this letter is 140 μs, similar to those used in Refs. [9,10]. By contrast, Belikov *et al.*[7] used a pulse width of 400 μs. The influence of the pulse duration of the Er:YAG laser system on the ablation threshold for dental enamel was discussed by Apel *et al.*[10]. The threshold shift induced by different pulse widths in the range from 100 to 700 μs is of one order of magnitude of the fluctuation resulted from local differences in the composition of dental tissue samples. Moreover, a shift may be observed in the lower limit of onset of ablation when the pulse duration is shorter. The thermal loss mechanism is a function of time; thus, larger amounts of energy diffuse into the surrounding tissue with longer pulse widths. Lower ablation thresholds are observed when shorter pulse durations are used.

Additional factors arise from the method used to determine the ablation threshold. The principles and equipment used in each determination method vary. Considering the inhomogeneity of biological tissues, the thresholds determined by probability statistics are believed to closely approximate actual values. However, the definition may differ even in this method. Apel *et al.*[10] determined thresholds based on a probability of 80%, whereas Kang *et al.*[9] employed a probability of only 50%. Furthermore, differences in the determination criteria for the occurrence of ablation may have an important function in the thresholds obtained. Kang *et al.*[9] defined the ablation threshold as the incident radiant exposure that induced either mass ejection or surface disruption. In this letter, tissue removal is taken as the exclusive standard of ablation occurrence; tissue

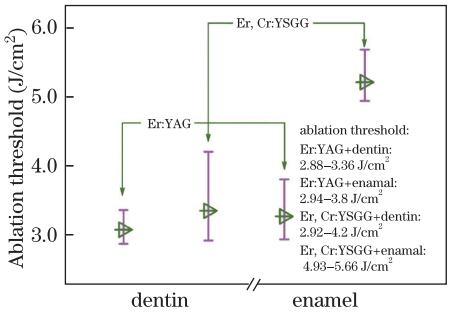

Fig. 5. Ablation threshold ranges for dental tissue irradiated by the Er:YAG and Er,Cr:YSGG lasers.

Table 2. Ablation Thresholds of Dental Hard Tissues Published in Different Reports

Laser	Tissue	Reference	Threshold J/cm^2	Method / Pulse Width
Er:YAG	Enamel	Apel[10]	10 (9–11)	Probability Statistics (80%), 150 μs
	Enamel	Hibst[6]	10	Theoretical Calculation
	Enamel	Fried[16]	7–9	Experimental Estimates, 150 μs
	Enamel	Belikov[7]	7	Experimental Estimates, 400 ms
	Enamel	Present Work	3.27 (2.94–3.8)	Probability Statistics (80%), $\sim$ 200 μs
	Dentin	Farrar[14]	5.2	Curve Fitting
	Dentin	Hibst[6]	10	Theoretical Calculation
	Dentin	Present Work	3.08 (2.88–3.36)	Probability Statistics (80%), $\sim$ 200 μs
Er,Cr:YSGG	Enamel	Apel[10]	13 (10–14)	Probability Statistics (80%), 150 μs
	Enamel	Kang[9]	1.2/2.1	Probability Statistics (50%), 100 μs
	Enamel	Belikov[7]	4	Experimental Estimates, 400 ms
	Enamel	Present Work	5.2 (4.93–5.66)	Probability Statistics (80%), 140 μs
	Dentin	Present Work	3.35 (2.9–4.2)	Probability Statistics (80%), 140 μs

degeneration is not regarded as a sign of ablation. As such, the thresholds determined in this letter are higher than those in Ref. [9].

Due to the complex nature of dental tissue, the ablation threshold cannot be determined as an exact value and is instead presented as a range. In this context, a sensitivity of 80% during statistical analysis is adopted in this study. Such a sensitivity indicates that ablation may take place in a specific portion of a sample when irradiated with an energy density lower than the ablation threshold. The appearance of ablation at doses lower than the threshold may be clearly observed in some specimens by SEM.

The ablation thresholds of both lasers in enamel are higher than those in dentin, as shown in Fig. 4. The results closely correlate with the composition and absorption properties of the dental materials investigated. While enamel and dentin are composed of the same materials, the proportions of these materials vary significantly between the samples. Enamel contains, by volume, 12% water, 3% proteins and lipids, and 85% minerals composed mainly of hydroxyapatite. Dentin is composed of 20% water, 33% proteins and lipids, and 47% minerals[17]. The water component in the tissues strongly absorbs laser energy and induces micro-explosions that blast away minuscule particles of hard tissues because of the considerable overlap between the wavelength of the Er lasers and the water absorption band. The water content in dentin is almost twice that in enamel. Therefore, more laser energy is necessary to remove enamel while less energy is necessary to remove dentin. Differences in the ablation thresholds of enamel and dentin may also be due to variations in the structures of the samples. Dentinal tubules are arranged in an orderly manner, and the structure of dentinal tubules contributes to their porosity.

Compared with the Er,Cr:YSGG laser, the thresholds of the Er:YAG laser for enamel and dentin for are lower. This difference may be attributed to variations in the absorption coefficients and dynamics at the individual wavelengths of the lasers. The absorption coefficient μ_a of enamel at 2.94 μm is 800 cm^{-1}, twice that at 2.78 μm (480 cm^{-1})[17]. Moreover, the wavelengths of the Er:YAG and Er,Cr:YSGG lasers correspond to free water and OH^- groups within the mineral molecule, respectively. The near-instantaneous vaporization of free water at 2 940 nm and the transfer of conductive heat from apatite to free water at 2 780 nm may contribute to the different thresholds of the two lasers. A water spray was provided during Er,Cr:YSGG laser irradiation. External water absorbs laser energy and consequently induces a higher ablation threshold. However, a water film of certain thickness promotes the effectiveness of ablation[18]. The role of external water in ablation must be clarified in further studies.

In conclusion, the ablation thresholds of Er:YAG and Er,Cr:YSGG laser radiation for dental enamel and dentin are systematically evaluated using probability statistics. Under the tested conditions, the ablation thresholds of the Er:YAG laser for dentin and enamel are determined to range from 2.88 to 3.36 J/cm^{2}and from 2.94 to 3.8 J/cm^2, respectively. The ablation thresholds of the Er,Cr:YSGG laser for dentin and enamel are slightly higher and range from 2.92 to 4.2 J/cm^2 and from 4.93 to 5.66 J/cm^2, respectively. These findings suggest that the ablation threshold range of enamel is higher than that of dentin and that the threshold of the Er:YAG laser is lower than that of the Er,Cr:YSGG laser. The ablation thresholds vary with the type of dental tissue and the type of laser used.

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