외부의 물과 Er:YAG Laser의 작용에 의한 Dental Hard Tissue에서의 열과 역학적 효과: Free-running 방식

권 용 훈[1], C. J. Frederickson[2], M. Motamedi[3], S. Rastegar[1]

Exogenous-Water-Induced Thermal and Mechanical Effects on Dental Hard Tissue by the Er:YAG Laser: Free-running Mode

Y. H. Kwon[1], C. J. Frederickson[2], M. Motamedi[3], S. Rastegar[1]

1 Texas A&M University, College Station, TX 77843, U.S.A.

2 MicroFab Technologies, Inc., Plano, TX 75074, U.S.A.

3 University of Texas Medical Branch, Galveston, TX 77555, U.S.A.

Abstract

This study was performed to understand the exogenous-water-drop induced thermomechanical effect on the tooth in the free-running Er:YAG laser mode for the proper use of water as a laser energy absorber and coolant in dentistry.

The free-running Er:YAG laser was used in the dental hard tissue ablation study. A Microjet system was employed to dispense precise water drops. Ablation rate, recoil momentum, and temperature rise in the pulp cavity were measured with and without an exogenous water drop on the tooth surface.

Exogenous water enhanced ablation rate in the thick tooth in which the ablation rate on the dry surface does not increase linearly but shows plateau. Optimal exogenous water volume was shifted from 2 nl to 4 nl as the laser energy was increased from 48 mJ to 145 mJ. The magnitude of the recoil momentum was increased as the volume of exogenous water increased.

The results of this study suggest that we must pay attention to the recoil momentum or recoil pressure study for the optimal and safe usage of water in the dental treatement because these mechanical effects depend on the volume of exogenous water on the tooth surface.

Introduction

Recently there has been some research on the use of nontoxic dye solutions for tissue welding and hard tissue ablation in conjuction with Near Infrared (NIR) lasers [1-3]. This research is based on the fact that dental hard tissue absorbs light poorly in the visible and near-IR wavelengths. As a result, laser light penetration and absorption are very low in dental tissues. In addition, laser light absorption at the tooth surface is not uniform because of the hydroxyapatite matrix and the varying thicknesses of enamel and dentin within each tooth. In order to overcome target material's poor laser absorption, exogenous absorbers were sprayed on the target surface to enhance laser absorption and to confine energy absorption to a small volume. The combination of indocyanine green dye and an Alexandrite laser has been shown to enhance tissue welding [3] and hard tissue ablation [1,2]. Our motivation in this present research was to use a simple absorber, water, in conjuction with the Er:YAG laser at whose wavelength with absorption property of water is near its peak value. This method enables researchers to overcome the insufficient light absorption from laser irradiation due to the different absorption peaks of the target materials.

When a plume of material is ejected at high velocity during the laser ablation process, it imparts recoil momentum [4,5]. The generated recoil momentum propagates as pressure waves. During the course of impact and the propagation of pressure waves, crater and/or mechanical damage occurs in the material. The effect of the recoil momentum induced by water assisted laser ablation in dentistry is not fully understood in terms of safety and ablation efficiency.

The goal of this study was to understand the effect of controlled exogenous-water-drop-enhanced thermal and mechanical effects on the tooth. Ablation rate, recoil momentum were investigated to establish the feasibility of controlled-volume-of-water-assisted Er:YAG laser ablation in dentistry.

Materials and Methods

Ablation Rate Study

The free-running Er:YAG laser (Schwartz Electro-Optics, model 1-2-3, wavelength = 2.94 μm) was used in the ablation rate study. The laser energy delivered per pulse was measured using a joulemeter (Coherent, model LMP10), and ranged from 30 mJ to 145 mJ per pulse. In this study the volume of exogenous water was an important parameter. It was possible to precisely control a water drop by employing a precise piezoelectric fluid dispensing device called a Microjet system (Microfab Tech, Plano, TX) . The Microjet system can dispense a pre-set amount of water ranging from 200 pl to 400 nl. Distilled and then filtered water was used for the exogenous water drop in the experiment. The dispensed water drop and incident laser beam were aligned to hit the same position on the target surface in order to maintain consistency and reliability in the measurement. The samples used were healthy sections of extracted human molars. They were sliced along the longitudinal direction with a slow-speed diamond saw. The thickness of each slice and its mass were measured using a micrometer (Starrett Co, #722) and a digital scale (Mettler Instrument Co, PC440) prior to the experiment. The number of laser pulses required to penetrate the sample was counted.

Recoil Momentum Study

The recoil momentum was measured using a beam-type pendulum. Figure1 shows the experimental setup for the measurement of recoil momentum. When the focused Er:YAG laser beam hits the surface of the target, the pendulum swings slowly. A HeNe laser was used to monitor the pendulum's deflection angle. The HeNe laser beam initially was aimed to hit a small mirror on the top of the pendulum. The reflected HeNe beam then was directed onto a screen. The pendulum's movement caused the spot to oscillate in the longitudinal direction and its movement was recorded using a CCD camera and a VCR. The recoil momentum can be defined as follows [5]:

$$P = I\omega a_{max}/x = (\sqrt{M^2L^2gs}/\sqrt{3x^2}) \cdot a_{max}$$

where I is the pendulum's moment of inertia ($=ML^2/3$), M is the total mass of the pendulum including the sliced tooth, L is the length of the pendulum, ω is the oscillation frequency ($=\sqrt{Mgs/I}$), g is the gravitational acceleration, s is the distance between the rotation axis and the center of mass, x is the distance between the rotation axis and the impact point of the laser beam on the target, and a_{max} is the maximum deflection angle. Measurements were performed for two different surface conditions: dry surfacce and surface with exogenous-water-drop.

Results

Ablation Rate Study

The ablation rates for different laser energies versus number of water pulses on enamel are presented in Figs. 2 and 3 respectively.

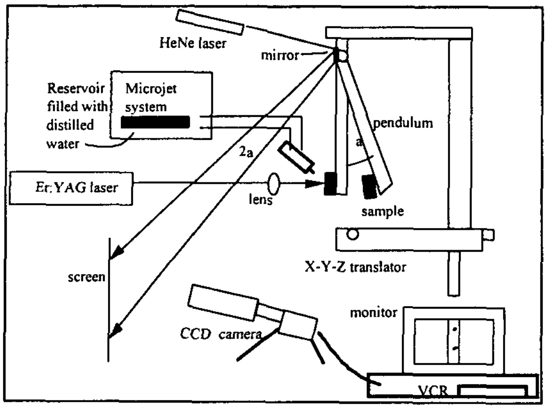

Figure 1. Experimental setup for the measurement of recoil momentum.

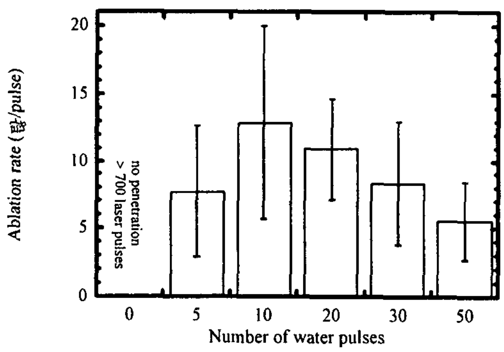

Figure. 2. *Ablation* rate on enamel at 48 mJ. The volume of one water pulse was 200 pl. The thickness of the slice was 1 mm.

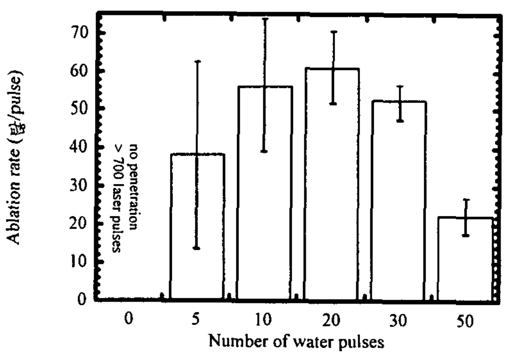

Figure. 3. Ablation rate on enamel at 145 mJ. The volume of one water pulse was 200 nl. The thickness of the slice was 2.3 mm. The energy of laser was 145 mJ.

The volumes of the water drops dispensed on the surface were 0 (dry), 1 nl, 2 µl, 4 nl, 6 nl, and 10 nl. As clear in the figures the ablation rate was affected by the exogenous water greately for different laser energies. Penetration of the tooth without exogenous water was not possible even with sufficiently large number of laser pulses. On the other hand, the ablation rate was increased as the number of water pulses, in other words as the volume of exogenous water drop, increased and then it was decreased after passing one optimal number of water pulses. For lower laser energy (48 mJ), the optimal volume of exogenous water drop was 2 nl. As the laser energy was increased the optimal volume shifted to the larger volume such that it was 4 nl for higher laser energy (145 mJ). And also, the ablation rate was increased about 5 times (from 13 µm/pulse to 61 µm/pulse) as the laser energy was increased about 3 times (from 48 mJ to 145 mJ) though the thickness of a tooth slice was increased more than two times (from 1 mm to 2.3 mm). Each bars in the figure show high standard deviation for different number of water pulses. The standard deviations were ranged from 9% (minimum) to 64% (maximum) in the overall ablation rates. Through the study it was shown that an exogenous water drop enables the laser pulse penetrates the given thick tooth slice in which the ablation rate of the dry surface does not increase but makes platea

Recoil Momentum Study

Plots of the recoil momentum induced by the ablating material versus fluence for different surface conditions are shown in Figures. 4a and 4b. The recoil momentum was linearly related to the fluence of the incident laser pulses at any exogenous water volume (0, 40 nl, 200 nl, and 400 nl). As the volume of exogenous water increased, the volume of vaporizing water also increased and as a result the recoil momentum increased. The recoil momentum in dentin was greater than that in enamel at any exogenous water volume. It was attributed to the difference in the ablation rates. Since the ablation rate in dentin was greater than that in enamel, more mass was removed from the dentin.

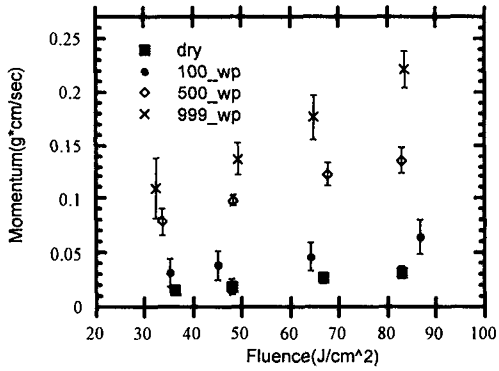

Figure. 4a. Recoil momentum versus fluence for enamel with and without exogenous water on the enamel surface. The volume of 1 wp was 400 pl.

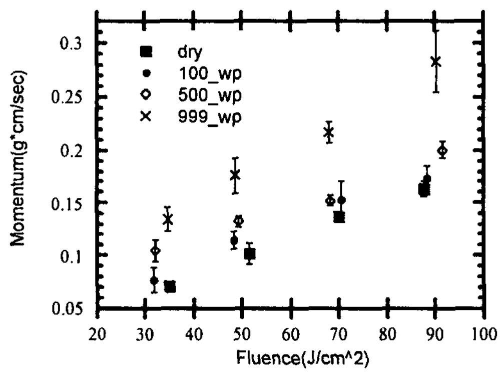

Figure. 4b. Recoil momentum versus fluence for dentin with and without exogenous water on the dentin surface. The volume of 1 wp was 400 nl.

Discussion

The nature of the Er:YAG laser-induced ablation rate of dental hard with and without an exogenous water drop can partially be understood by taking into account the normal-spiking-mode Er:YAG laser pulse and the ablation of water. The absorption coefficient for pure water in the 2.94 μm wavelength is approximately 13,000 cm^{-1} , and the heat of vaporization for room-temperature water is 2.26 kJ/cm^3. From these values it is estimated that about 0.2 J/cm^2 is enough to initiate vaporization of pure water. So a small portion of the incident energy readily generates the explosive vaporization of water because of very high absorption coefficient of water. The explosive vaporization of water puts a recoil force onto the tooth surface and digs a cavity if there is any remaining water. The remainder of the incident laser pulse passes through this cavity and is absorbed into the underlying tooth. As the volume of exogenous water increases, the laser energy absorbed for water ablation increases, and the remaining laser energy decreases. The condition for the optimal exogenous water volume will be determined in such a way that it should maximize the coupling of laser energy with water and minimize consumption of laser energy to ablate the given exogenous water on the tooth.

Since exogenous water assisted ablation allows better coupling of laser energy to the tooth in terms of mechanical energy required to ablate tooth so much of the energy is used for the ablation of tooth (and exogenous water) and then diffused as heat. This is why the repeatedly dispensed small amount of exogenous water drop on the tooth enables the laser to penetrate the tooth and lowers temperature rise in the pulp cavity. Unlike exogenous water assisted ablation, the depth of the crater on the dry tooth increases as the number of pulse increases and then it makes plateau after some number of pulses. The reason of this plateau is not clear. Partially it is believed due to the defocusing of the focused beam and the geometry of a crater.

When the ablation generates the ejection of particles and water vapor, the force of the ejection causes a recoil momentum on the surface of the tooth. If ablation products are scattered at an average flying velocity, they cause a linear recoil momentum. In a pendulum, this linear recoil momentum shows up as a rotational recoil momentum. Accuracy of the evaluation of the recoil momentum mainly depends on two parameters: deflection angle, and the distance between the screen and mirror. The range of experimental error which took place in the measurement of deflection angle was 2%-8%.

The amplitudes of the recoil momentum created by the exogenous water drop on the tooth were higher than those of the dry surface case. The reason is mainly due to the ablation process. The water drop on the tooth was removed completely from the surface during one macro pulse. The mass removed from enamel or dentin by one laser pulse can be estimated if we assume the crater has a cone shape. Roughly calculated by this assumption, removed mass was 6 μg. This estimated mass is smaller than the mass of the smallest water drop, 40 μg, that we used in experiments. It is clear from this rough estimation that recoil momentum depends mainly on the mass of the exogenous water drop. As a result, recoil momentum increases as the volume of the exogenous water drop increases. Though an increased water volume raises the amplitude of the recoil momentum, it does not mean the higher recoil momentum is better.because the recoil momentum can act as the source of unwanted mechanical damage. So the greater the recoil momentum, the higher the recoil pressure and greater unwanted thermal and mechanical damage will be on the tooth. In the aspect of safety it is important to find an optimal volume for the exogenous water drop on the tooth surface in order to minimize unexpected mechanical damage on the tooth and temperature rise in the pulp cavity

Conclusion

We have studied the thermomechanical effect induced by an exogenous-water-drop on the tooth during laser ablation. An exogenous water drop on the tooth acts as an absorber such that it enhanced the ablation rate compared to the dry surface case. The ablation rate and the volume of exogenous water were correlated so finding an optimal exogenous water volume was very important to maximize the ablation rate. In our system, 2 nl of water drop was optimal for lower energy (48 mJ) and it was shifted to larger volume as laser energy increased. For higher energy (145 mJ), 4 nl was optimal for maximum ablation rate. An exogenous water assisted ablation of hard tissue is effective in the thick tooth in which the ablation rate on dry surface does not increase but make plateau after some number of laser pulses. Control the volume of exogenous-water-drop is an important factor which may affect the mechanical damage on the tooth. Our study shows that the recoil momentum induced by the tooth ablation depends on the volume of the exogenous water on the tooth surface such that as the volume of exogenous-water-drop increases, the amplitude of the recoil momentum increases.

References

1. R. O. Esenaliev, A. A. Oraevsky, M. Motamedi, S. Rastegar, F. K. Tittel, "Mechanism of dye-enhanced pulsed laser ablation of hard tissues: Implications for dentistry", IEEE STQE, 2, pp. 836-846, 1996

2. E. Jennett, M. Motamedi, S. Rastegar, C. Frederickson, C. Arcoria, "Dye-enhanced ablation of enamel by pulsed lasers", J Dent Res, 73, pp. 1841-1847, 1994

3. S. D. DeCoste, W. Farinelli, T. Flotte, R. R. Anderson, "Dye-enhanced laser welding for skin closure", Lasers Surg Med, 12, pp. 25-32, 1992

4. J. A. Fox, "Effect of water and paint coatings on laser irradiated targets", Appl Phys Lett, 24, pp. 464-466, 1972

5. R. Hibst, "Mechanical effects of Er:YAG laser on bone ablation", Lasers Surg Med, 12, pp. 125-130, 1992