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Study on elucidation of bactericidal effects induced by laser beam irradiation Measurement of dynamic stress on laser irradiated surface

Tatsuaki Furumoto [a,*], Atsushi Kasai [b], Hiroshi Tachiya [a], Akira Hosokawa [a], Takashi Ueda [a]

[a] *Institute of Science and Engineering, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan*
[b] *Graduate School of Natural Science and Technology, Kanazawa University, Kakuma-machi, Kanazawa, Ishikawa 920-1192, Japan*

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ABSTRACT

In dental treatment, many types of laser beams have been used for various surgical treatments, and the influences of laser beam irradiation on bactericidal effect have been investigated. However, most of the work has been performed by irradiating to an agar plate with the colony of bacteria, and very few studies have been reported on the physical mechanism of bactericidal effects induced by laser beam irradiation. This paper deals with the measurement of dynamic stress induced in extracted human enamel by irradiation with Nd:YAG laser beams. Laser beams can be delivered to the enamel surface through a quartz optical fiber. Dynamic stress induced in the specimen using elastic wave propagation in a cylindrical long bar made of aluminum alloy is measured. Laser induced stress intensity is evaluated from dynamic strain measured by small semiconductor strain gauges. Carbon powder and titanium dioxide powder were applied to the human enamel surface as absorbents. Additionally, the phenomenon of laser beam irradiation to the human enamel surface was observed with an ultrahigh speed video camera. Results showed that a plasma was generated on the enamel surface during laser beam irradiation, and the melted tissues were scattered in the vertical direction against the enamel surface with a mushroom-like wave. Averaged scattering velocity of the melted tissues was 25.2 m/s. Induced dynamic stress on the enamel surface increased with increasing laser energy in each absorbent. Induced dynamic stresses with titanium dioxide powder were superior to those with carbon powder. Induced dynamic stress was related to volume of prepared cavity, and induced stress for the removal of unit volume of human enamel was 0.03 Pa/mm^3.

1. Introduction

Laser beams have several unique properties that make them useful for a variety of applications in dental treatment, such as a substitute of a rotary cutting instrument, to increment acid resistance of enamel, and as a scalpel for soft tissues [1–3]. Recently, there has been considerable interest in bactericidal effect induced by laser beam irradiation. Schultz et al. [4] investigated the influence of Nd:YAG laser beam irradiation on bactericidal effects on *Staphylococcus aureus*, *Escherichia coli*, and *Pseudomonas aeruginosa*. They concluded that input energy with laser beam irradiation was related to the bactericidal effects. Bergmans et al. [5] tested the hypothesis of bactericidal effect with Nd:YAG laser irradiation on endodontic pathogens inoculated in root canals ex vivo. They reported that Nd:YAG laser irradiation is not an alternative but a possible supplement to protocols for disinfection as the unique properties of laser beams may allow bactericidal effect beyond the reach of traditional preparation. Ando et al. [6] evaluated the bactericidal effects of Er:YAG laser irradiation on periodontopathic bacteria, and concluded that high energy irradiation was effective for sterilization of the bacteria. Sterilization of bacteria has been reported with various laser beams, such as an excimer laser in the ultraviolet region [7,8], a diode laser in the near infrared region [9], and a carbon dioxide laser in the infrared region [10]. Additionally, Schoop et al. [11] investigated the influence of various laser beams, such as Nd:YAG, diode, Er:YAG, and Er,Cr:YSGG lasers, on the bactericidal effects with indirect laser irradiation using sliced dentins. They concluded that all the wavelengths investigated were suitable for disinfection of even deeper layers of dentin.

When the specimen is irradiated with laser beams, laser induced stress intensity is generated around the irradiated area [12,13]. There has been a consideration that sterilization of bacteria might be caused by the mechanical effects induced by laser beam irradiation [14]. However, very few studies have been reported on the mechanism of bactericidal effects induced by laser beam irradiation. The final goal of our study is to solve the mechanism of bactericidal effects induced by laser irradiation. Elucidation of sterilization mechanisms makes an effective clinical proposal with laser beam irradiation possible. This paper

* Corresponding author.
E-mail address: furumoto@t.kanazawa-u.ac.jp (T. Furumoto).

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deals with the measurement of dynamic stress induced by Nd:YAG laser beam irradiation on extracted human enamel. Dynamic stress induced in the specimen is measured using elastic wave propagation in a cylindrical long bar made of an aluminum alloy. Laser induced stress intensity is evaluated from dynamic strain measured by small semiconductor strain gauges. The influence of irradiation conditions and absorbents applied to the surface of extracted human enamel on induced dynamic stress is evaluated experimentally. Additionally, the aspect of cavity preparation on the extracted human enamel is observed with an ultrahigh speed video camera.

2. Theory of elastic wave propagation in long bars

A schematic illustration of elastic wave propagation in a cylindrical long bar is shown in Fig. 1. It is assumed that length of the long bar is large enough compared with its diameter and the other end of the long bar has free boundary. When a dynamic stress $\sigma(t)$ is loaded at the end of the long bar, an induced elastic wave travels without any change in form so long as diameter of the long bar is small compared with length of the induced elastic pulse and the long bar is not stressed [15]. Therefore, dynamic stress $\sigma_A(t)$ at point A after time t_0 is expressed by following formula [16,17]:

$$\sigma(t) = \sigma_A(t+t_0) \tag{1}$$

Velocity C_0 of elastic wave propagation is dependent on the bar material, and is given as follows:

$$C_0 = \sqrt{\frac{E}{\rho}} \tag{2}$$

where E is Young's modulus and ρ is the density of the long bar. Thus, time t_0 in formula (1) is obtained as follows:

$$t_0 = \frac{l_0}{C_0} \tag{3}$$

where l_0 is the distance from the end of the long bar to point A. From Eqs. (1)–(3), the waveform at the end of the long bar is obtained by transferring the waveform at point A for the time interval t_0.

When the traveling elastic pulse wave reaches the other end of the long bar, the sign of the pulse wave is changed; that is, the tension pulse that emerges is the same as the incident compression pulse.

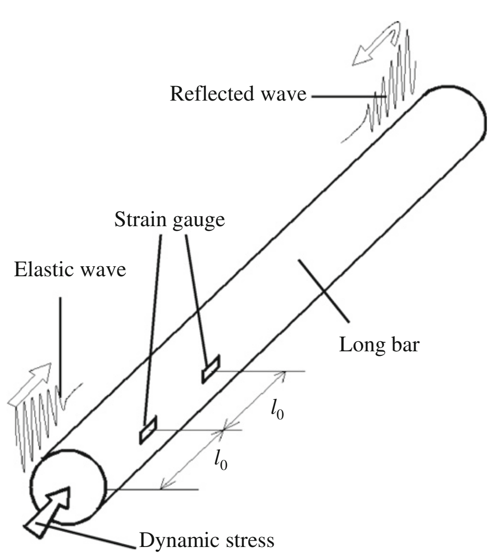

Fig. 1. Schematic illustration of elastic wave propagation.

Therefore, added stress at the end of the long bar is expressed as follows:

$$\sigma(t) = \sigma_L(t) + \sigma_R(t) \tag{4}$$

where $\sigma_L(t)$ is the compression pulse wave traveling to the right side and $\sigma_R(t)$ the tension pulse wave traveling to the left side. When the distance from point A to point B is the same as l_0, dynamic stress $\sigma_A(t)$ at point A and $\sigma_B(t)$ at point B are given, respectively, as follows:

$$\begin{aligned} \sigma_A(t) &= \sigma_L(t-t_0) + \sigma_R(t+t_0) \\ \sigma_B(t) &= \sigma_L(t-2t_0) + \sigma_R(t+2t_0) \end{aligned} \tag{5}$$

From (1)–(5), dynamic stress loaded at the end of the long bar is calculated as follows [16]:

$$\sigma(t) = \sigma_A(t+t_0) + \sigma_A(t-t_0) - \sigma_B(t) \tag{6}$$

Therefore, dynamic force loaded at the end of the long bar can be determined from the measurement of dynamic stress at point A and point B.

3. Experimental setup and conditions

3.1. Laser facility

In this study, a pulsed Nd:YAG laser facility (Altech Co., Ltd.—STREAK I), which is mainly used for dental treatment, is used. The specifications of this facility are given in Table 1. The wavelength is $\lambda = 1064$ nm and irradiation energy per pulse and pulse duration can be adjusted precisely. A laser beam is irradiated to a target through a quartz optical fiber of core diameter 400 μm and numerical aperture $NA = 0.37$. The intensity of laser beam relative density measured by beam profile system (OPHIR Corp.—Beam star FX-50) is shown in Fig. 2. The laser beam used to measure the profile was a He–Ne laser of laser power $P = 1$ mW. The distance from the edge face of optical fiber to the measured position was 5.6 mm. The beam profile at the edge face of the optical fiber was calculated using the beam profile obtained from the measurement. As shown in the graph, the laser beam formed a Gaussian shape and the diameter at the edge of the optical fiber was $\phi = 226$ μm.

3.2. Observation of enamel surface with ultrahigh speed video camera

To investigate aspects of cavity preparation during laser beam irradiation, a human enamel surface was observed by an ultrahigh speed video camera (Shimadzu Corp.—HPV-1). The experimental conditions are given in Table 2. The recording speed of video camera was 250,000 fps and resolution was 312 pixels in the horizontal direction and 260 pixels in the vertical. As a light source, stroboscopic flash (Sugawara laboratories Inc.—ESD-VF2M-U2) was used. The specimen used was extracted human

Table 1
Specifications of the laser facility.

Laser		Nd:YAG (PW)
Wavelength	λ	1064 nm
Peak power	P	1–4 kW
Irradiation energy	E_l	50–990 mJ/pulse
Pulse duration	τ	50, 100, 200, and 400 μs
Frequency	f	1–99 Hz
Optical fiber		Quartz
Core diameter	ϕ_c	400 μm
Numerical aperture	NA	0.37