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Ablation of demineralized dentin using a mid-infrared tunable nanosecond pulsed laser at 6 µm wavelength range for selective excavation of carious dentin

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Abstract— **In dental clinic, some lasers have already realized the optical drilling of dental hard tissue. However, conventional lasers lack the ability to discriminate and excavate carious tissue only, and still depend on the dentist's ability. The objective of this study is to develop a selective excavation of carious dentin by using the laser ablation with 6 µm wavelength range. Bovine dentin demineralized with lactic acid solution was used as a carious dentin model. A mid-infrared tunable pulsed laser was obtained by difference-frequency generation technique. The wavelength was tuned around the absorption bands called amide 1 and amide 2. In the wavelength range from 5.75 to 6.60 µm, the difference of ablation depth between demineralized and normal dentin was observed. The wavelength at 6.02 µm and the average power density of 15 W/cm^2, demineralized dentin was removed selectively with less-invasive effect on normal dentin. The wavelength at 6.42 µm required the increase of average power density, but also showed the possibility of selective ablation. In the near future, development of compact laser device will open the minimal invasive laser treatment to the dental clinic.**

I. INTRODUCTION

Applications of lasers in dentistry have become widespread since they can offer more comfortable and precise dental treatments. In clinic, Er:YAG laser (λ = 2.94 µm) and Er,Cr:YSGG laser (λ = 2.78 µm) have already realized the optical drilling of dental hard tissue with minimal thermal damage. On the other hand, a highly preservative approach to dental caries management, called minimal intervention dentistry (MI) [2], has been proved to have the best chance for the survival of natural tooth structure. Extension for prevention [3] is no longer a tenable concept according to current knowledge of the caries process and the developments of adhesive materials. Although the selective excavation of infected dentin is required, conventional lasers lack the ability to discriminate and excavate carious tissue only, and still depend on the dentist's treatment ability [4].

Regulation of laser parameters to optimize laser-tissue interaction has high potential for selective caries excavation. In particular, a wavelength selection primarily affects mechanisms of the interaction. Conventional dental lasers have the wavelengths near 3 µm which strongly absorbed by water. As a result of the strong absorption, the rapid vaporization of water and the accelerated water droplets drive tissue removal efficiently [5]. However, excessive laser-tissue interaction leads to non-selective ablation. Neves et al. have reported that Er:YAG laser excavation guided by the laser-induced fluorescence feedback system could not be considered a selective caries-removal technique compared with other dental excavation tools [6].

Based on the absorption property of dentin, the wavelength range around 6 µm and 9 µm are candidates for selective excavation. The wavelengths near 9 µm, which strongly absorbed by calcium phosphate, are not appropriate because normal dentin is excavated more than demineralized dentin. Caries-infected dentin could be regarded as a soft tissue because it lack a hard tissue based on calcium phosphate. The organic matters of carious dentin have a characteristic absorption bands called amide 1 and amide 2 in 6 µm wavelength range. That's why our group made the hypothesis that an irradiation with 6 µm wavelength range in low power density showed a promising feature for effective excavation of carious dentin. The hypothesis that an irradiation with low power density realized a less-invasive effect to a hard region such as normal dentin was also made. It is believed that these

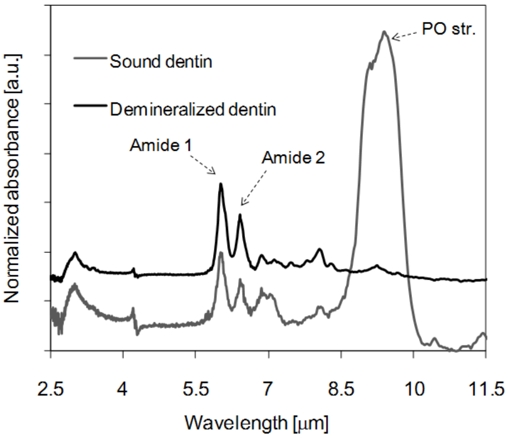

Fig. 1. Mid-infrared absorption spectra of normal (lower gray line) and demineralized dentin (upper black line). The spectra were normalized by the peak of amide 1. The baseline of demineralized dentin spectrum was slided for easy visualization.

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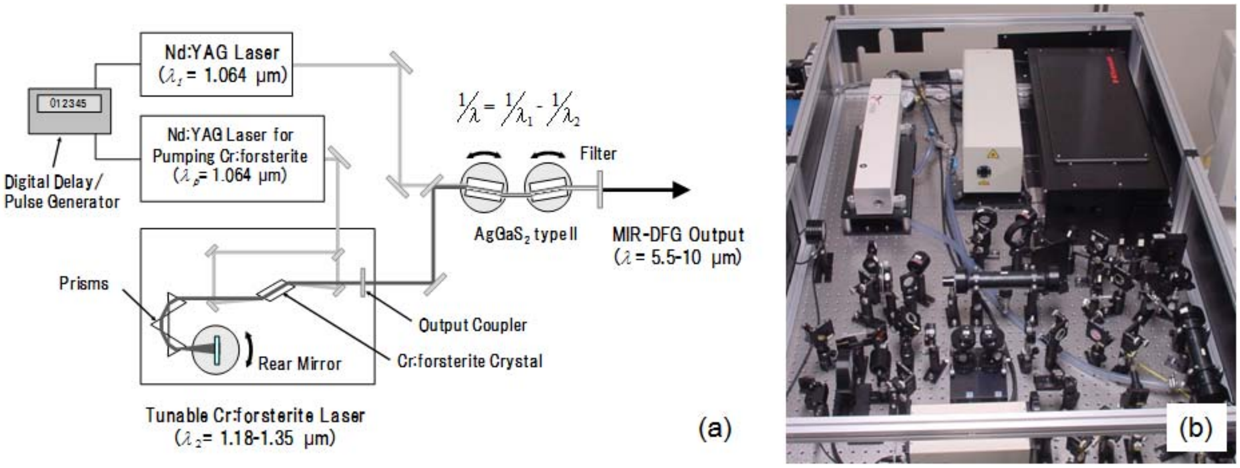

Fig. 2. Mid-infrared tunable nanosecond pulsed laser by difference-frequency generation. (a) optical setup. (b) overview.

hypotheticals realize the difference of excavation between normal and carious dentin.

The objective of this study is to develop a selective and minimal invasive excavation technique of carious dentin for realizing next generation laser dentistry and MI dentistry. The fundamental utility of a laser ablation with 6 µm wavelength range for selective excavation of carious dentin was investigated using a mid-infrared tunable pulsed laser. This study focused on two points, the wavelength dependency of ablation at 6 µm wavelength range and the comparison of 6.02 µm and 6.42 µm which corresponded to absorption bands called amide I and amide II, respectively.

II. MATERIALS AND METHODS

A. Sample

Bovine teeth were cut and ground to prepare dentin plates approximately 5×5×1 mm^3. As a model of carious dentin, dentin plate was demineralized with 0.1 M lactic acid solution for 24 hours [7]. Demineralization was performed at 37 degrees centigrade with stirring. The infrared absorption spectra of demineralized dentin (carious dentin model) and normal dentin were shown in Figure 1. Before laser irradiation, samples were dehydrated under reduced pressure for an hour.

B. Light Source

A difference-frequency generation (DFG) is a promising wavelength conversion approach to generate a mid-infrared (MIR) wavelength. MIR tunable nanosecond pulsed laser by difference-frequency generation (MIR-DFG) was used in this study. The prototype of the MIR-DFG was developed by RIKEN and Kawasaki Heavy Industries, Ltd. [8].

Figure 2 showed the schematic of the MIR-DFG optical setup. The MIR-DFG wavelength range (5.5-10 µm) was obtained by DFG between a Q-switched Nd:YAG laser with a wavelength of 1064 nm (Tempest 10, New Wave Research, Inc., USA) and the tunable Cr:forsterite laser pumped by a Q-switched Nd:YAG laser (Tempest 300, New Wave Research, Inc., USA) within a wavelength range of 1180-1350 nm. The wavelength of the Cr:forsterite laser was varied by rotating the rear mirror of the optical resonator and measured with a wavelength meter (WS5-IR, HighFinesse GmbH, Germany). A digital delay/pulse generator (DG535, Stanford Research Systems Inc., USA) was used to synchronize the Nd:YAG and the Cr:forsterite laser pulses. Two $AgGaS_2$ crystals with a same dimension and same cutting angles were used in order to obtain high output energy and to compensate a displacement of the optical axis.

The MIR-DFG radiations tuned to some wavelengths in 6 µm wavelength range were used to irradiate the sample plates. In the experiment resulted in Figure 3, irradiated wavelengths were tuned from 5.60 to 6.60 µm at 0.05 µm interval. In the experiment resulted in Figure 4 and 5, irradiated wavelengths were tuned at two pattern, 6.02 and 6.42 µm. The MIR-DFG delivers 5 ns pulse width. The pulse repetition rate was set to 10 Hz. An electronic shutter (F77-4, Suruga Seiki, Japan) controlled the irradiation time from 0, 1, 2, 4, 5 and 8 s. The average power was measured with a power meter just before laser irradiation. Samples were located horizontally on a irradiation stage and irradiated by the beam focused using a parabolic mirror (f = 100 mm). The beam diameter (FWHM size) was measured by knife-edge method. The average power densities were set to 15, 20 and 22 W/cm^2.

C. Evaluation

After laser irradiation, gold coating was applied on samples using an ion sputtering device (E-1010, HITACHI, Japan) and the ablation crater was observed with a scanning electron microscope (JCM-5700, JEOL, Japan) to evaluate the surface morphology. Analysis of the ablation crater size was performed with a confocal laser microscope (LEXT OLS3000, Olympus, Japan).

III. RESULTS AND DISCUSSION

A. *Wavelength dependency of ablation at 6 µm wavelength range*

Figure 3 showed the ablation depth of normal and demineralized dentin with an average power density of 20 W/cm^2 and an irradiation time of 5 s in the wavelength from 5.60 to 6.60 µm at 0.05 µm interval. It was indicated that the ablation tendency in this wavelength range was similar to the absorption property of organic matter because an absorption maximum was observed around a wavelength at 6.00 µm, which derived from amide 1 absorption band.

In the wavelength range from 5.75 to 6.60 µm, the difference of ablation depth between demineralized and normal dentin was observed. This difference leads to the treatment selectivity. In the wavelength at 6.00 µm, maximum ablation depth was observed in a demineralized dentin. However, ablation of normal dentin was also observed. In the wavelength from 5.75 to 5.85, ablation of demineralized dentin without an ablation to normal dentin was achieved. This result suggests that the wavelength which is not an absorption maximum is suitable for selective ablation.

B. *Comparison of 6.02 µm and 6.42 µm*

Figure 4 showed the ablation depths of normal and demineralized dentin with an irradiation time from 1 to 8 s. Irradiation condition in figure 4(a) was an average power density of 15 W/cm^2 and a wavelength at 6.02 µm. The wavelength at 6.02 µm with an average power density of 15 W/cm^2 ablated demineralized dentin selectively [9]. In same irradiation energy condition, the wavelength at 6.42 µm induced less ablation than 6.02 µm. The wavelength at 6.42 µm required a higher average power density for the same ablation ability as 6.02 µm. Figure 4(b) showed the result in an irradiation condition with a wavelength at 6.42 µm, an average power density of 22 W/cm^2. The increase of average power density improved the ablation depth by a wavelength at 6.42 µm.

Figure 5 summarized the morphological changes after laser irradiations. Normal and demineralized dentin irradiated by 6.02 µm showed smooth morphologies in the ablation crater (Figure 5(a)). In contrast, marked melting of demineralized dentin and cracking of normal dentin were found at the irradiated surface by 6.42 µm (Figure 5 (b)). Therefore, a wavelength of 6.02 µm with an average power density of 15 W/cm^2 was determined to induce more suitable interaction in terms of efficiency and less thermal side effect.

A wavelength of 6.42 µm, which corresponds to the absorption band of amide II, is reported to be effective for biological soft tissue cutting [10]. In our study, a wavelength of 6.42 µm exhibited lower ablation ability than a wavelength of 6.02 µm. Unique composition of hard tissue, absence of water during laser irradiation, or low average power density setting seemed to affect the result. Simply considering absorption property of an organic matter only, absorbance of

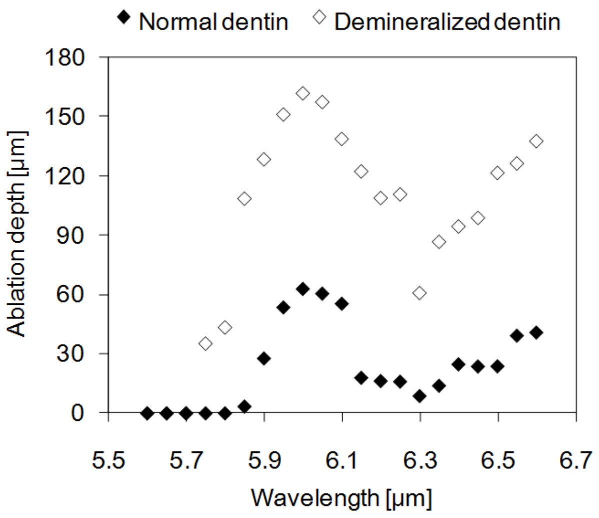

Fig. 3. Ablation depth of normal and demineralized dentin in the wavelength from 5.6 to 6.6 µm.

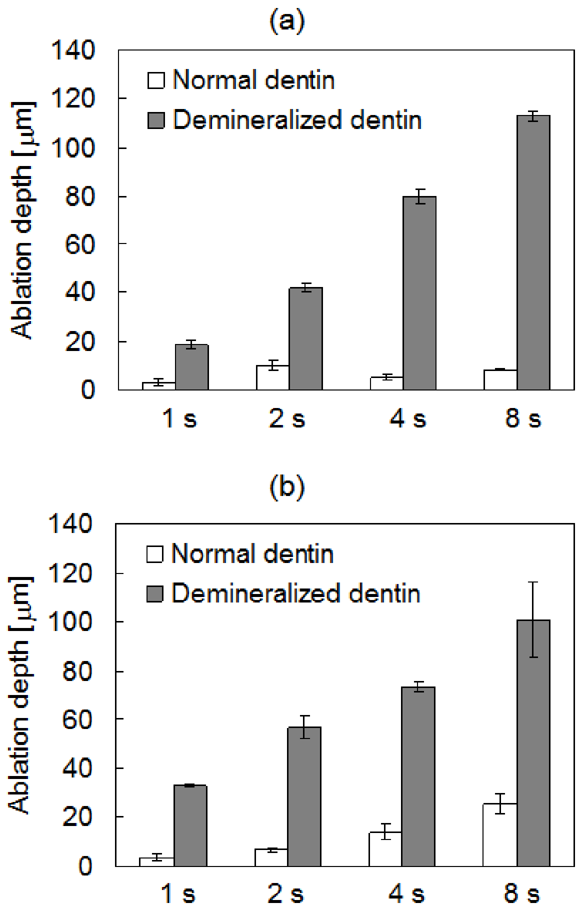

Fig. 4. Ablation depth versus irradiation time. (a) wavelength; 6.02 µm and average power density; 15 W/cm^2. (b) wavelength; 6.42 µm and average power density; 22 W/cm^2.

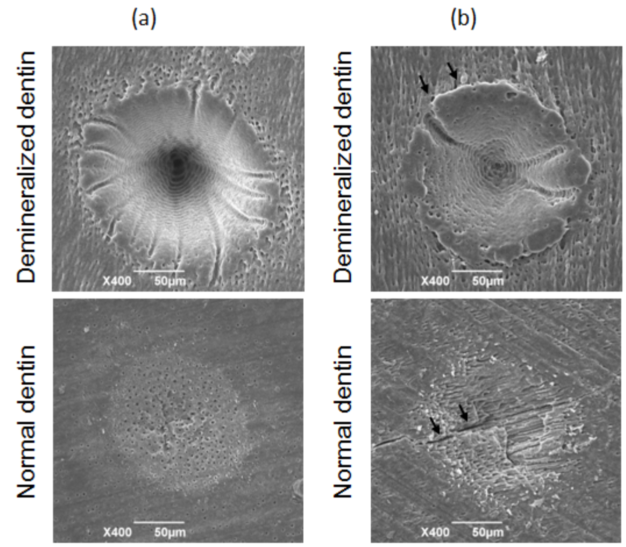

Fig. 5. Surface morphologies of demineralized and normal dentins after 8 s laser irradiations. (a) wavelength; 6.02 μm and average power density; 15 W/cm^2. (b) wavelength; 6.42 μm and average power density; 22 W/cm^2. The arrows in demineralized dentin (b) show a melting. The arrows in normal dentin (b) show cracks.

6.02 μm is 1.5 times as large as that of 6.42 μm, which might lead to higher thermal confinement and more effective ablation behavior.

On the other hand, an importance of primary absorber of laser energy has been supposed. The wavelength range around 6μm is easy to receive the effect of water, which has a strong absorption. This study was conducted in a dry surface condition. So it must be confirmed by future works using 6 μm wavelengths with water, which is a competitive absorber with organic matters.

Our group has estimated that the selective excavation using lasers mainly depends on a difference of the mechanical property between normal and demineralized dentin. Wavelength choice is also important. The wavelength derived from absorption of minerals is unusable because normal dentin is ablated more than demineralized dentin. Er:YAG laser with a wavelength of 2.94 μm already has been served in dental clinic all over the world. Use of a commercial Er:YAG laser at the average power density of 70~90 W/cm^2 without water spray also resulted in selective ablation in our study. But, an irradiation without water spray causes a serious thermal side effect because of its long pulse width. The improvement of a pulse width by Q-switched Er:YAG laser is required for a better selective excavation by using a Er:YAG laser.

The laser with 6 μm wavelength range has not been popular. However, the technique about a quantum cascade laser, which is a compact mid-infrared semiconductor laser, has rapidly advanced in recent years. This technique will open the minimal invasive laser treatment with 6 μm wavelength range.

IV. CONCLUSION

Ablation ability of 6 μm wavelength range was investigated with the goal to optimize selective caries excavation. In the wavelength range from 5.75 to 6.60 μm, the difference of ablation depth between demineralized and normal dentin was observed. A wavelength at 6.02 μm yielded more effective ablation than 6.42 μm. In future works, further regulations of laser parameters and irradiation methods (pulse width, pulse repetition rate, and cooling method etc.) will determine the best condition for the selective laser caries treatment. Furthermore, the combination of compact laser device and optical fiber for mid-infrared wavelength region will open the minimal invasive laser treatment to the dental clinic in the near future.

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