Study on Use of Blue-violet Laser Diode Module as Dental/Oral Surgical Device

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Laser has been used widely in surgical treatment of oral tissues that are easy to bleed, because of its ability to incise tissues with hemostasis. Among different kinds of dental lasers, CO_2 laser and near-infrared diode laser are especially widely used. CO_2 laser beam is highly absorbed by water and therefore is able to efficiently incise soft tissues that contain much water. On the other hand, near-infrared diode laser features compactness and ease of use. In recent years, violet laser diode has been developed and practically used as the light source of next-generation DVD systems. The authors focused attention on violet laser diode's oscillating wavelength (405 nm), which is around the peak of the absorption spectrum of hemoglobin, and has developed a violet laser diode module for use in dental and oral surgeries. The experiments confirmed that this module provides efficient tissue incision performance and faster healing equivalent to that of CO_2 laser. It was also confirmed that the module is suitable for use in teeth bleaching and killing of periodontopathic bacteria. From these experiment results, the authors expect that the violet laser diode module will be used as a next-generation multifunctional dental laser. This paper reports on the study of the application of violet laser diode module to dental/oral treatment.

1. Introduction

Laser equipment is capable of performing ablation and incision while providing hemostasis, and is widely used in intraoral surgery where bleeding can often occur[1]. One of the oldest types of laser equipment is CO_2 laser. The wavelength of CO_2 laser (10.6 μm) is strongly absorbed by water, which means that CO_2 laser is suitable for efficient ablation and incision of soft tissues that contain large amounts of water. Therefore, CO_2 lasers are widely used for the treatment of inflamed areas of the body. Laser diodes began to be considered as tools for surgical treatment of soft tissues only in the 1990s when technologies for high power laser diodes were established[2]. Nowadays, AlGaAs and InGaAs laser diodes are the most widely used laser diodes. Their wavelengths (810-980 nm) are within the ranges called "treatment window" or "diagnostic window"[3] and are not absorbed easily by any substances contained in the human body. Therefore, AlGaAs and InGaAs lasers can penetrate deeply into tissues. This characteristic of these laser lights to penetrate deep into tissues makes them very effective in hemostasis by forming a thick thermally coagulated layer. In addition to the coagulation effect, these lasers are used to perform ablation and incision by contacting the tip of its output fiber to the tissue[4]. Moreover, laser diodes can be made smaller compared to CO_2 lasers, which is an advantage in clinical applications.

The commercialization of GaN blue-violet laser diode in 1999 was a significant advancement in the recent history of laser diodes. GaN blue-violet laser diode's light output (405 nm wavelength) interacts with the substances in the living body in such a way that it is absorbed greatly by hemoglobin, and its absorption by melanin is greater by more than one order of magnitude than in the case of near infrared light[5]. Hemoglobin transports oxygen in blood. Large quantities of hemoglobin are found in intraoral tissues where there are many capillaries. Large quantities of melanin also exist on gum tissue surfaces. Therefore, the authors are researching blue-violet laser diode's application into oral surgeries[6], and also its germicidal effect against periodontal disease-causing bacteria as well as its teeth whitening capability. This research is motivated by the facts that bacteria causing periodontal diseases strongly absorb short-wavelength visible light[7] and that there are teeth whitening agents that strongly absorbs short-wavelength visible light[8].

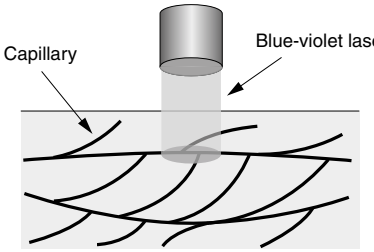
This paper covers the results of the following three application studies on blue-violet laser diodes: (1) ablation and incision of soft body tissues, (2) sterilization of periodontal disease-causing bacteria, and (3) teeth whitening.

2. Ablation and incision of soft body tissue

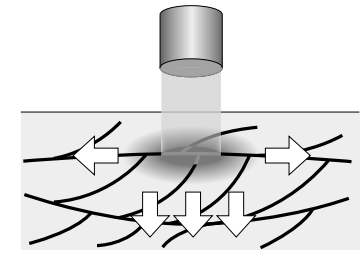
2-1 Overview

Interactions of laser light with living body tissue include photochemical interaction, thermal interaction, photoablation and photodisruption. The mechanisms of these interactions depend on conditions such as wavelength, power density, and duration of interaction[5]. It is said that most of the reported cases of ablation of living tissues were done through thermal interactions, except for the cases where photoablation was used to correct nearsightedness by removing a selective amount of corneal tissue using an ArF excimer laser (λ = 193 nm). Thermal interaction is a phenomenon in which the light is absorbed by biomolecules, causing the temperature of the tissue to rise due to the conversion of light energy to heat and resulting in the vaporization of

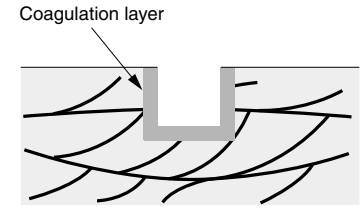
water within the tissue. The expansion of water during vaporization causes pressure to be applied to the tissue and breaks it up into fragments that eventually vaporize along with water. The authors assumed that when a blue-violet laser beam is irradiated on living body tissue, the beam is absorbed by proteins such as hemoglobin to cause an effective ablation. **Figure 1** shows the schematic diagram of the ablation mechanism.



(a) A blue-violet laser light is absorbed by protein (such as hemoglobin or collagen) or by pigment (such as melanin).



(b) The tissue is heated to 100˚C, and the vaporization of water causes the pressure in the tissue to increase.



(c) The tissue is ablated.

Fig. 1. Mechanism of soft tissue ablation using blue-violet laser beam

2-2 *In vitro* experiment

As the first step in studying the ablation and incision of soft tissue using a blue-violet laser diode, the authors observed the change in the lean flesh of tuna when it was irradiated by a blue-violet laser beam. **Figure 2** shows the experimental setup.

The end of the output optical fiber of the blue-violet laser diode module was coupled with a lens so that the light is focused onto the sample surface. The diameter of the focused beam was 240 μm. The sample was placed on the motorized stage and scanned at the speed of 1mm/s, which mimics the speed of hand movement of a dentist during surgical treatment. After being irradiated with laser light, the sample was cut perpendicular to the scanning direction and the depth of incision was measured using a stereomicroscope. The reason tuna

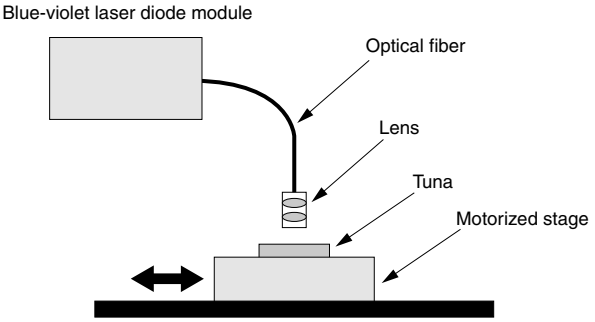


Fig. 2. Experimental setup of soft tissue ablation by blue-violet laser

flesh was chosen as the experimental sample was that tuna fish has well-developed muscle and therefore is rich in myoglobin that has a similar absorption spectrum as hemoglobin. This feature makes tuna fish a suitable alternative to intraoral tissue that is rich in capillaries. **Figure 3** shows the measured absorption spectrum of the tuna flesh used in the experiment. As can be seen from the figure, there is an absorption peak near 415 nm, and the absorption coefficient at 405 nm was 2.3 [1/mm].

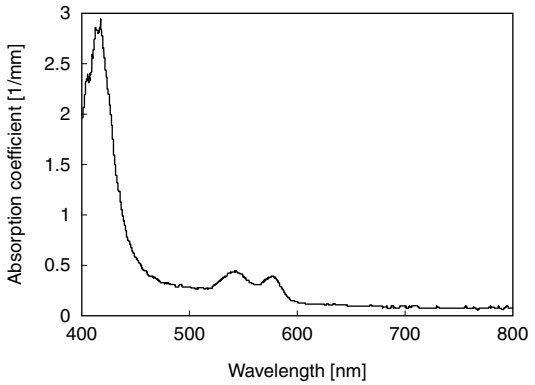


Fig. 3. Absorption spectrum of tuna flesh

Figure 4 is the experimental result showing the relationship between irradiation power and incision depth. For comparison purpose, a similar experiment was conducted using a near-infrared laser diode whose wavelength was 930 nm. The diameter of the incident beam was 100 μm, which was smaller than that of the beam from the blue-violet laser diode (240 μm), which yields the power density of about 5.8 times stronger than that of a blue-violet laser diode of the same output power.

As seen from this chart, the ablation threshold of the blue-violet laser diode was about 400 mW, while the 930 nm near-infrared laser diode only yielded some degree of whitening and shrinkage and no ablation even at the maximum output power of the laser used for the experiment, which was 4.4 W. Thus, it has been verified that the blue-violet laser is capable of ablating and incising soft tissue with a relatively lower power compared to the near-infrared laser.

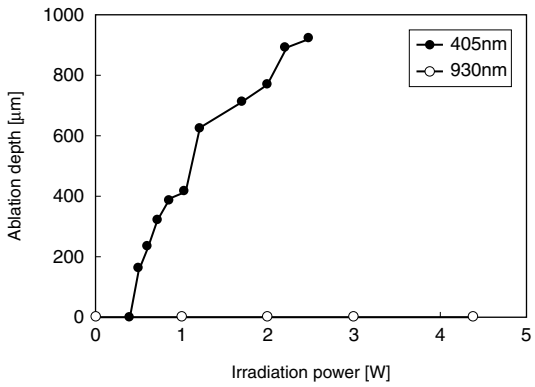


Fig. 4. Depth of incision made by blue-violet laser beam

2-3 *In vivo* experiment

It has been verified in an *in vitro* experiment that the blue-violet laser diode can efficiently ablate and incise tuna fish tissue. However, the tensile strength of tuna fish tissue was not the same as those of living body tissue, and there is no blood circulation in sample tuna flesh. Therefore, as the next step, the tongues of Wistar rats were incised with the blue-violet laser diode to evaluate the laser performance. The irradiation power was set at 1.7 W, and the beam diameter and the scan speed were set as the same as those in the *in vitro* experiment. **Figure 5** shows a Wistar rat's tongue incised with the laser beam.

Fig. 5. Rat's tongue incised with blue-violet laser beam

A deep ablation/incision of tissue is observed at the center of the tongue. At the periphery of the incision, a brown coagulated layer and a white degenerated layer are seen. There was no bleeding at all during and after the incision. **Figure 6** shows a cross section of the incised tongue tissue.

The figure shows a large U-shaped ablated layer of a high aspect ratio with its width of 100-160 μm and depth of about 800 μm, which are roughly the same as the groove made in the *in vitro* experiment. Because the tongue is essentially a chunk of muscle, it contains a large quantity of myoglobin. Moreover, capillaries exist in the tongue, so hemoglobin is also contained. It is inferred that these substances strongly absorbed the blue-violet light, which generated heat locally to cause the ablation. It has been thus confirmed in both *in vivo* and *in vitro* experiments that the blue-violet laser beam has the strong ablation and incision capabilities as well as the strong hemostatic capability.

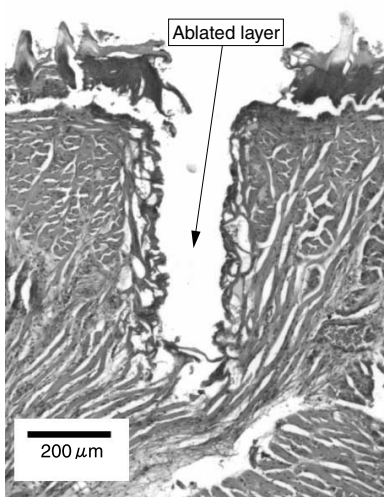


Fig. 6. Cross-section of rat's tongue after incision by blue-violet laser beam

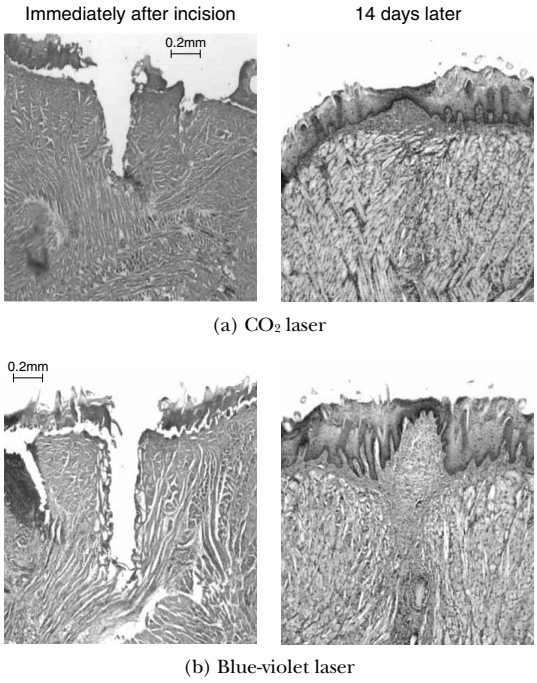


Fig. 7. Healing process after laser incision

The length of healing period is one of the most important factors in practical application of laser equipment in surgical applications. Generally speaking, a near-infrared laser beam can penetrate deeply into tissue and causes the thermal denaturation of tissue over a large area, which results into slow healing. On the other hand, a CO_2 laser beam is absorbed near the surface layer of tissue and therefore its thermal effect is largely confined to the area near the ablated area, which results in faster healing[1]. **Figure 7** shows the photographs of the healing process on rat's tongues after they were incised with a blue-violet laser beam and a CO_2 laser beam.

The blue-violet laser diode beam made an ablated layer of about 800 μm deep immediately after the incision, which is deeper than the one made with the CO_2 laser beam (depth of about 520 μm). Fourteen days after the incision, however, the ablated layer was recovered by the formation of fibrous tissue and by the regeneration of the epithelial tissue in the same way as in the case of the ablated layer by the CO_2 laser beam. This verifies that the blue-violet laser diode provides a similar healing result as the CO_2 laser that is considered to provide a rapid healing among the currently used lasers for an even deeper incision. Based on these experimental results, it can be said that the blue-violet laser diode possesses a significant potential as a surgical laser incision tool in terms of incision capability and healing speed.

3. Sterilization of periodontal disease bacteria

3-1 Overview

As the society is aging, the number of people affected by periodontal diseases is expected to increase. Periodontal diseases are the biggest cause of losing teeth. Besides, it is becoming clear that periodontal diseases are closely connected to systemic illnesses such as cardiac diseases[9]. Porphiromonas gingivalis (P.g.), which is one of periodontal disease bacteria, is known to have its absorption peak around 400 nm. Experiments have been conducted to verify the sterilizing effect of the blue-violet laser beam on P.g.

3-2 Experimental method

P.g. ATCC 33277 was anaerobically cultured on blood agar media for three days. After this period, a suspension liquid was prepared with the colony and sterilized distilled water at a condition of OD660 = 0.45. The suspension liquid was then diluted 10^4- and 10^5-fold. The 10^5-fold diluted suspension liquid was used for the control group, and the 10^4-fold diluted suspension liquid was used for the laser treated group. The control group was not irradiated with laser light, and the laser treated group was irradiated with laser light in eight patterns as shown in **Table 1**.

1.0 μl of the diluted suspension liquid was delivered by drops onto a blood agar medium, irradiated with a laser light, and then spread evenly using a Conrage stick, followed by seven days of anaerobic culture. After the culture period, the amount of P.g. in each group was counted using the colony count method. The diameter of the laser beam was set at 5 mm so that the entire surface of the diluted solution delivered by drops can be irradiated. Considering the practical conditions with a possible thermal damage to the tissue, the maximum irradiation power was set at 400 mW.

Table 1. Laser irradiation conditions

Group	Irradiation Power [mW]	Irradiation Intensity [W/cm²]	Irradiation Time [sec]
A	100	5.1	10
B	100	5.1	20
C	200	10.2	10
D	200	10.2	20
E	300	15.3	10
F	300	15.3	20
G	400	20.4	10
H	400	20.4	20

Figure 8 shows the experimental results. This figure shows the average survival rate of bacteria (N = 10) for each group. Here, the bacterial survival rate is given as: (Average number of colonies in each laser irradiated group) / (Average number of colonies in the control group) * 100. The bacterial survival rate for group A was 28.5%, while that for group H was a very low value of only 1.4%; a higher light power and longer irradiation time produced a lower survival rate of bacteria. These results confirm that irradiating blue-violet laser light is effective in sterilizing P.g. The blue-violet laser diode module developed by Sumitomo Electric Industries, Ltd. is capable of having smaller output fiber diameters down to 165 μm, which makes it easy to irradiate selectively on periodontal pockets around teeth and tooth roots where bacteria grow in large numbers. This makes the blue-violet laser diode module even more powerful in actual clinical use.

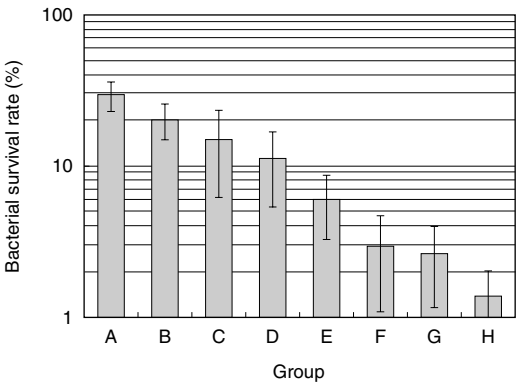


Fig. 8. Sterilizing effect of blue-violet laser light

4. Whitening of teeth

4-1 Overview

Interest and demand for aesthetic dental surgery is growing. Presently, the clinical dental practice of in-office bleaching of vital teeth often uses 35% hydrogen peroxide solution. This involves some risks such as damages to tooth substances and soft tissues; hence, the treatment should be done with caution. Recently, hydrogen peroxide bleaching agent including titanium dioxide has become commercially available, which allows the whitening of teeth to be carried out with a low concentration of hydrogen peroxide of only 3.5% when used in conjunction with a photocatalytic technology[7]. With attention focused on the fact that this bleaching agent strongly absorbs visible short-wavelength light, experi-

ments were conducted to study the teeth whitening effects of the combinations of this bleaching agent and blue-violet laser light.

4-2 Experimental method

Extracted bovine lower anterior teeth were used as specimens in the teeth whitening experiments. Laser irradiation was performed using three different light sources: a blue-violet laser diode at 400 mW (group A), a blue-violet laser diode at 200 mW (group B), and a high power halogen light source for curing of dental resins that peaks at around 460 nm at 500 mW (group C). Color change and whitening effect were determined by comparing the color difference (ΔE) after one minute, five minutes, and ten minutes of irradiation. The color difference was obtained using the L*a*b color space. The L*, a* and b* values were measured to obtain their changes between before and after the irradiation, ΔL*, Δa* and Δb*, and then the formula $\Delta E = (\Delta L^{*2} + \Delta a^{*2} + \Delta b^{*2})^{1/2}$ was calculated. **Figure 9** shows the results of the experiments.

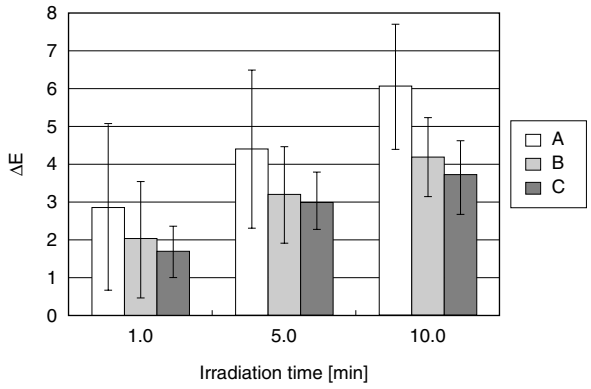


Fig. 9. Teeth whitening effect of blue-violet laser light

This chart shows the average (N = 8) color difference at each whitening condition. It has been found that a longer irradiation time yielded a greater color difference for each irradiated group. In addition, the groups irradiated with blue-violet laser light (groups A and B) yielded a greater color difference than the group irradiated with halogen light (group C). In particular, the group A treated with ten minutes irradiation had a high ΔE of 6.07. Generally speaking, a color difference of 6.0 or more is considered to have a visibly significant difference. Therefore, blue-violet laser diode can be considered also as a promising tool for teeth whitening.

5. Conclusions

It has been proven, though not at a clinical level, that blue-violet laser diode is a useful tool in (1) ablation and incision of soft tissue, (2) sterilization of periodontal disease bacteria, and (3) whitening of teeth. Unlike conventional laser equipment, this type of laser has multiple functions, and can be considered a promising dental surgery equipment of the future. At this point, the higher cost of blue-violet laser diode compared with near-infrared laser diode remains an issue. But this can be overcome as technology advances, and new dental laser equipment contributing to the improvement of quality of life (QOL) of patients may be developed.

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