Synchronous radiation with Er:YAG and Ho:YAG lasers for efficient ablation of hard tissues

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Abstract: Er:YAG and Ho:YAG laser beams were combined to irradiate hard tissues to achieve highly efficient ablation with low laser power. The delay time between pulses of the two lasers was controlled to irradiate alumina ceramic balls used as hard tissue models. With optimized delay time, the combined laser beam perforated the sample 40% deeper than independent radiation by either an Er:YAG or Ho:YAG laser. An ultra-high-speed camera and an infrared thermography camera were used to observe and investigate the ablation mechanisms.

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1. Introduction

Since the water that bio-tissues contain strongly absorbs infrared light, irradiation with infrared lasers has a strong effect on both hard and soft tissues and, therefore, is used in a variety of medical applications. In urological applications, such as treatment of enlarged prostate and fragmentation of urinary calculi, 2.1- μm wavelength Ho:YAG lasers are often used, and the laser light is delivered by common silica-glass fiber optics in a thin endoscope to irradiate inside the human body [1–4]. In dental applications, 2.94- μm wavelength Er:YAG lasers are often used [5] because the wavelength coincides with a water absorption line [6], which enables highly efficient ablation of hydroxyapatite, which contains a large amount of water [7].

It has also been reported that more effective fragmentation of urinary calculi is possible with Er:YAG lasers [8] because the laser light is strongly absorbed by the calcium oxalate and magnesium ammonium phosphate in urinary calculi [9,10]. However, flexible silica-glass optical fibers cannot be used for delivery of Er:YAG lasers because of the absorption loss of silica in the 3- μm wavelength region. To solve this problem, optical fibers made of infrared transmission glasses such as germanium oxide [11] and fluoride glasses [12,13] have been proposed and developed for transmission of Er:YAG laser light. Although these glass fibers have low transmission losses, when transmitting high-powered lasers, they need special care on the input and output end surfaces because of fragileness of these glasses. Also, for germanium-oxide glasses, the output end should be spliced to silica fiber tip when used in water [14]. In contrast, hollow optical fibers are robust and have high energy transmission capability and they are also useful for laser application in water by putting a glass cap on the distal end [15]. We have developed hollow optical fibers that deliver radiation of both the Er:YAG and the Ho:YAG lasers with high efficiency [16] and they enable simultaneous delivery of these two lasers.

To increase ablation speed for hard tissues such as teeth and calculi, radiation with laser pulses with a high average power becomes necessary. However, this also generates heat in the vicinity of the irradiated part [17] that could cause damage or pain. To improve ablation speed with infrared laser light, here we investigate effects of synchronous irradiation with Ho:YAG and Er:YAG lasers for more efficient hard tissue ablation. Pratisto, *et al*, reported that, in hard-tissue ablation in water, ablation effect of Er:YSGG laser light ($\lambda = 2.79 \mu\text{m}$) is enhanced more than twice when an Er:YSGG pulse is radiated after a Ho:YAG laser pulse with a delay time of 100 μs . This is because the Ho:YAG creates a vapor channel in water [18,19] and Er:YSGG transmits in the channel with a low absorption loss. In this case, the Ho:YAG works only for creating vapor channel in water and it has no direct effect on ablation. In this paper, we try increasing the ablation effect for tissues that have wet surface. We synchronously radiate Er:- and Ho:YAG lasers in air and show that both lasers have different ablation effects.

With a proper delay in these two laser pulses, these ablation effects enhance each other and give higher ablation effect.

2. Experimental setup

We used the experimental setup shown in Fig. 1 to irradiate a hard tissue model with light from two different lasers. Since we assume a laser system with a flexible hollow-optical fiber, we use a hollow fiber that is available in market [20]. The fiber also acts as an optic to irradiate a single small spot with combined beam of the two lasers. Ho:YAG ($\lambda = 2.1 \mu\text{m}$) and Er:YAG ($\lambda = 2.94 \mu\text{m}$) laser beams are combined with a dichroic mirror and the combined beam is focused by a $f = 100 \text{ mm}$ CaF_2 lens on the input end of a hollow optical fiber. The inner diameter of the fiber is 0.7 mm and the length is 30 cm . The inside surface of the hollow fiber is coated with silver and cyclic-olefin polymer (COP) thin film. The thickness of the COP is $0.3 \mu\text{m}$ so that the transmission losses for both Er:YAG and Ho:YAG lasers are reduced by the interference effect of the polymer film that acts as a reflection enhancement coating [21]. The transmission losses of the 30-cm long hollow optical fiber used in the experiment were 1.0 dB for Ho:YAG and 0.5 dB for Er:YAG laser light.

Fig. 1. Experimental setup with dual-wavelength laser.

The distal end of the hollow optical fiber is capped to protect the inside of the fiber from vapor and debris from the ablated tissues [15]. We used hemispheric silica glass caps [22]. The focusing effect of the caps enables highly efficient ablation due to the high energy intensity at the focal point. Figure 2 shows the laser beam diameters measured from burn patterns on thermal paper. The focal length of the cap is around 0.8 mm from the end surface for both lasers and the insertion loss is around 10% for the Ho:YAG and 15% for the Er:YAG laser. The difference is due to absorption by silica glass, which is slightly higher for Er:YAG laser light.

Fig. 2. Laser beam sizes measured from burn patterns.

The laser emission timing and repetition rates of the pulses of the two lasers are controlled by an external trigger source and a delay line. To evaluate the ablation capabilities, we radiated lasers onto alumina (Al_2O_3) ceramic balls used as a hard tissue model and human tooth samples. When alumina balls have been soaked in water for more than 24 hours, the water content and density are compatible to dentin and enamel of human tooth. We used a thermographic camera with 350-frame/sec of capture speed and an ultra-high-speed camera with 50,000-frame/sec capture speed to observe the ablation phenomena and investigate their mechanisms.

3. Experiment

3.1 Laser ablation

First, we irradiated alumina balls with Ho:YAG and Er:YAG laser pulses independently and measured the widths and depths of the ablated holes on the alumina balls. The diameters of the alumina balls were 4 to 6 mm. The balls had been soaked in water for more than 24 hours prior to the experiment and had water content of 5–10% by weight. The laser pulses used in the experiment for both lasers had 200 mJ of pulse energy, widths of 250 μs , and repetition rates of 3 Hz. The measured depths and widths as a function of number of pulses are shown in Fig. 3. Cross sections of the ablated holes after 30 pulses are shown in Fig. 4. The error bars show measurement accuracy.

Fig. 3. Widths and depths of ablated holes as a function of number of laser pulses.

Fig. 4. Cross sections of alumina balls after ablation of 30 pulses.

Although the widths of the two lasers are comparable (Fig. 3), the depths are clearly different. When irradiated with the Ho:YAG, the depth saturated at large pulse numbers. This is because the energy density of the laser beam becomes lower than the ablation threshold of hard tissues when the beam spreads behind the focus spot. For the Er:YAG, in contrast, the

depth increases linearly with the number of pulses because the energy density of the laser beam always exceeds the ablation threshold due to the higher absorption coefficient in water for the Er:YAG laser light.

In the next experiment, to investigate the ablation capabilities, we measured the weight decrease of the alumina balls after laser ablation. The balls were fixed on the table and we irradiated the surface, randomly changing the irradiated spot without a water supply. The pulse widths were 250 μs for Ho:YAG and 300 μs for Er:YAG, and the irradiation time was 1 minute with a repetition rate of 10 Hz (600 pulses applied in total). Figure 5 shows the weight decreases of alumina balls as a function of pulse energy. The data show the average values of 10 measurements with different samples. As shown in Fig. 5, the weight linearly decreased with pulse energy and the ablation capability of the Er:YAG was two or three times higher than that of the Ho:YAG laser. This is apparently due to the difference of absorption in water of the two lasers.

Fig. 5. Weight decreases of alumina balls after laser irradiation.

3.2 Ablation with two lasers

Next we investigated the ablation effect of synchronously irradiating with both lasers. We changed the delay time between the two lasers and observed the effect on the ablation of alumina balls. Both lasers had pulse energies of 100 mJ and pulse widths of 250 μs at a repetition rate of 3 Hz. We compared the ablation depths with those made by the Er:YAG alone with a pulse energy of 200 mJ.

Figure 6 shows cross sections of alumina balls after 40 pulses (20 pulses for each laser) with delay times of -100, 0, and 200 μs . Positive delay time means that the Ho:YAG was emitted before the Er:YAG. Figure 7 shows the depths of ablated holes after 10 pulses as a function of the delay time. It is clear that the depths are highly dependent on the delay time. When irradiated with a delay time of ± 500 μs or less, depths drastically changed with the delay. The smallest depth was obtained at the delay time of -100 μs , and the obtained depth was 25% smaller than those made by radiation with the Er:YAG laser alone. On the other hand, the deepest ablation was obtained at the delay time of 200–300 μs and the ablated hole was 40% deeper. In another experiments measuring weight decrease of the samples after laser radiation, we had results that are similar with the ones with ablation depth. Therefore we use ablation depth for evaluation of ablated volume in this paper. Figure 8 shows the measured depths ablated by a dual-wavelength laser with a delay time of 200 μs as a function of number of pulses. Data for radiation with the Er:YAG laser alone are also shown for comparison. Depths ablated by the dual-wavelength laser increased rapidly after only a few pulses.

Fig. 6. Cross sections of alumina balls ablated by dual-wavelength laser with a delay time of (a) -100 μs , (b) no delay, (c) 200 μs .

Fig. 7. Ablation depths of alumina balls as a function of delay time.

Fig. 8. Ablation depths of alumina balls as a function of number of pulses.

3.3 Observation

To investigate the ablation mechanism shown in Fig. 7, we observed the ablation phenomena using an ultra-high-speed camera. We irradiated alumina balls with laser pulses and recorded the moment of ablation at the surface at 50,000 frame/sec. Figures 9(a) and 9(b) show ablations with (a) Er:YAG and (b) Ho:YAG lasers alone. Figure 9(c) is the moment of an Er:YAG pulse that was shot 200 μ s after a Ho:YAG pulse. When the sample was irradiated with Er:YAG laser light, powdery dust scattered from the surface immediately. This is because the laser energy was absorbed in the outermost surface of the ball. On the other hand, for the Ho:YAG laser, relatively large debris was scattered. The laser beam penetrated the ball and an explosive ablation occurred from the inside.

When a Ho:YAG pulse was shot after an Er:YAG, powdery dust generated by the Er:YAG blocked the Ho:YAG pulse [23,24]. As a result, the smallest depth was obtained with a delay time of -100 μ s, as shown in Fig. 7. In contrast, when an Er:YAG pulse was emitted after a Ho:YAG pulse [Fig. 9(c)], large fragments were scattered. In this case, the Ho:YAG pulse gives ablation effect free from dust from ablation with the Er:YAG.

Fig. 9. Moment of ablation with Ho:YAG and Er:YAG lasers

Next, we used a thermographic camera to observe heat generation during ablation of the alumina balls. Figure 10 shows thermal images of cross sections of balls 3 ms after laser radiation. When the Er:YAG laser was used, heat generated from the laser beam stayed at the surface. In contrast, with the Ho:YAG laser, laser energy penetrated deeper and heat diffused over a large area. This was due to the difference of absorption coefficients and is one of the

reasons why the ablation with Ho:YAG occurred from the inside as shown in Fig. 9(b). At the optimum condition in Fig. 7, where the Er:YAG emitted 200 μ s after the Ho:YAG, the heat was generated in a deeper area before the Er:YAG pulse. This decreased the absorption coefficient of water and the Er:YAG laser beam penetrated deeper into the ball, which led to ablation from within the ball.

From these results, it is seen that the Ho:YAG laser apparently plays a part in ablation. Ho:YAG laser light penetrates deeper into the tissue and causes ablation from deeper area in contrast to Er:YAG laser light that is strongly absorbed and ablates the tissue from the outmost surface. When these two lasers are simultaneously radiated, ablation from the surface and deeper area occur in the same time. Furthermore, they have synergetic effects in ablation. Heat generated by the Ho:YAG pulse that is radiated on ahead decreases the absorption coefficient of water at 2.94- μ m wavelength [25,26], and the Er:YAG can penetrate deeper and ablate the tissue from deeper area. However, this synergistic effect is limited by debris induced by laser light. If the debris on the laser path can be perfectly removed, we can irradiate two lasers just simultaneously to the tissue, which will lead to stronger ablation effect. We are now trying to remove the debris by spraying water during the ablation and the result will be reported elsewhere.

Fig. 10. Thermal images of cross sections of balls after laser pulse irradiation.

3.4 Dental ablation

We also applied dual-wavelength laser radiation to human teeth. Human teeth were sliced into 0.3-mm-thick pieces and soaked in water before the experiment. The same ablation experiments as above were performed, and we used an ultra-high-speed camera to observe the ablation phenomena on the dentin surface. Figures 11(a) and 11(b) show the ablation phenomena with (a) Er:YAG and (b) Ho:YAG lasers alone. Figure 11(c) is the moment of an Er:YAG pulse shot 200 μ s after the Ho:YAG. This ablation was similar to the one observed for alumina balls (compare to Fig. 9), and there was also a synchronous radiation effect for the two lasers.

Fig. 11. Moment of ablation of dentin with Ho:YAG and Er:YAG lasers.

Figure 12 shows a cross section of human dentin after 5 pulses of laser irradiation with a repetition rate of 3 Hz. Ablation effects for the tooth samples were similar to those for the alumina balls. At the optimum condition described above, we obtained 25% deeper ablation than in the tooth irradiated with Er:YAG only.

We used an optical microscope to investigate the surface condition of dental tissues after laser ablation. Figure 13 shows the surface of the dentin after sole radiation of Ho:YAG and Er:YAG, and dual-wavelength laser radiation of these. With the Ho:YAG, the surface is thermally damaged and carbonized in contrast to the surface radiated with the Er:YAG that has no damage. When irradiated with combination of these two lasers, the surface had a little thermal damage that is due to heat generated by the Ho:YAG. Since the surface of the dental tissue was not cooled in this experiment, the thermal damage will be largely reduced by applying water cooling.

Fig. 12. Cross section of human dentin after laser irradiation.

Fig. 13. Surface of dentin after laser ablation.

4. Conclusion

Laser ablation experiments were performed on hard tissues using a combined beam of Ho:YAG and Er:YAG laser light. Alumina balls were used as a hard-tissue model and ablation phenomena were observed with an ultra-high-speed camera. The two lasers had different ablation effects due to the different absorption coefficients in water contained in the tissues. When the two lasers were combined to irradiate the sample, ablation capabilities were highly dependent on the delay time between the pulses of the two lasers. When the Er:YAG laser radiated 200 μs after the Ho:YAG, the ablated hole was 40% deeper.

With combination of these two lasers, ablation from the surface that is with Er:YAG and deeper area with Ho:YAG occur in the same time. Furthermore, heat generated by the Ho:YAG pulse that is radiated on ahead decreases the absorption coefficient of water at the Er:YAG wavelength. Then the Er:YAG can penetrate deeper and ablate the tissue from deeper area. The same ablation effects were seen on human dentin; sharp, deep holes were ablated in the dentin at the optimum condition.