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RESEARCH ARTICLE

Comparison of diode laser in soft tissue surgery using continuous wave and pulsed modes *in vitro*

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Abstract In this study, the interaction between diode laser radiation and chicken soft tissue was studied *in vitro* by a high-speed digital video camera. We used a diode laser with a wavelength of (980 ± 10) nm and average power of 10 W. The diode laser was operated in continuous wave (CW) and pulsed modes. In CW mode, the average laser radiation power was 10 W; in pulsed mode, the average laser radiation power was 10 W and the peak power was 20 W. Diode laser radiation was delivered to soft tissue (chicken meat) using a quartz optical fiber with either a clear distal end (clear tip) or a distal end containing an optothermal converter (hot tip). Application of the diode laser in pulsed mode resulted in crater depths and areas of collateral damage in soft tissue about 1.6 times greater than those observed in CW mode at treatment with the clear tip. Significant differences in the crater depth and collateral damage width of chicken meat were not found after hot-tip treatment with the diode laser in CW and pulsed modes. Soft tissue treated with the hot tip showed crater depths about 3.4 times greater than those observed after treatment with the clear tip. Hot tip treatment further resulted in collateral damage widths about 2.7 times lower than those obtained after treatment with the clear tip.

Keywords diode laser, thermo-optically powered surgery, hot tip surgery, laser surgery, soft tissue

1 Introduction

Lasers are widely used for soft tissue surgery [1–19], because they effectively cut soft tissues with good hemostasis [1–3]. CO_2 lasers ($\lambda = 10.6\ \mu m$) are considered the most popular gas lasers [1,4–7]. They have been successfully used in general surgery [1], oncology [3–5], otorhinolaryngology [1,5], dermatology [6], and dentistry [3,4]. Neodymium-doped yttrium aluminum garnet (λ = 1.064 or 1.320 μm) [1,7,8], holmium-doped yttrium aluminum garnet (λ = 2.1 μm), thulium-doped yttrium aluminum garnet (λ = 1.96 μm) [1,9], and erbium-doped yttrium aluminum garnet (λ = 2.94 μm) [1,10], as well as solid-state lasers, are frequently used for soft tissue surgery.

In recent years, the use of radiation from diode [1,7,11–19] and fiber [1,19] lasers for soft tissue surgery has attracted considerable interest. Diode laser radiation with a wavelength of (980 ± 10) nm is one of the most widely used lasers in dentistry and dermatology [14–18]. The average power of these lasers for medical application does not exceed 10–15 W [12–18], with rare exceptions [20,21].

Laser surgery refers to the cutting of soft tissue by the heat produced from absorption of laser energy. An optical fiber with a clear distal end (i.e., clear tip) can be used in contact or noncontact mode on biological tissue. Soft tissue components have weak absorption at 980 nm [22]; for example, the absorption coefficient of water is approximately $0.5\ cm^{-1}$ [23] while that of blood is 1.0–$2.0\ cm^{-1}$ [24]. The absorption coefficient of maxillary sinuses mucosa at the wavelength range of 950–1000 nm is approximately $0.4\ cm^{-1}$ [22], that of human skin is 0.2–$2.0\ cm^{-1}$ [22,25], and that of muscle tissue is $0.46-0.51\ cm^{-1}$ [25]. Thus, the speed and depth of tissue cutting by lasers are limited, and the collateral damage (e.g., coagulation, denaturation, and necrosis) induced by these lasers may be large [13,26].

Soft-tissue destruction can also occur from interactions between the tissue and an optothermal converter, also known as a hot tip; this type of tissue-cutting is called hot-tip surgery [27]. The optothermal converter or hot tip is placed at the distal end of the optical fiber. Laser radiation is absorbed by the optothermal converter, and this converter is heated to high temperatures [21,27]. In this

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case, soft tissue destruction occurs from heating by the optothermal converter. In some medical cases, a feedback system for the temperature control of optothermal converter and another system for automatic correction of the laser power are applied [28]. Thermo-Optically Powered surgery (TOP® surgery) technology has recently been developed [20,21,29]. Using this technology, the temperature of the optothermal converter can be maintained at a preset level during tissue treatment [20,29]. Most often, these converters are formed by adhesion to the distal end of the optical fiber; tissue fragments are then burned off during laser irradiation [27,30]. A similar process can be achieved by simple contact irradiation of some flammable materials, such as paper and wood [30–33]; specially designed automated irradiation of a unique target material has also been reported [21].

Numerous investigations on the interaction between diode lasers and soft biologic tissues are available [12–18,26,34]. However, these studies focus on the effectiveness of direct laser surgery, which is difficult to compare with hot-tip surgery. Comparative histological *in vitro* studies of the effects of conventional laser surgery and TOP® surgery on chicken meat soft tissue have been presented in previous studies [20,29]. Considering current limitations, more studies are necessary to determine which of the two technologies is capable of making deeper cuts with the same average laser radiation power while minimizing the area of collateral damage. To the best of our knowledge, comparative research on the influence of pulsed power on post-surgery tissue wounds between conventional laser surgery and hot-tip surgery with the same average power of diode laser at a wavelength of 980 nm has not been performed.

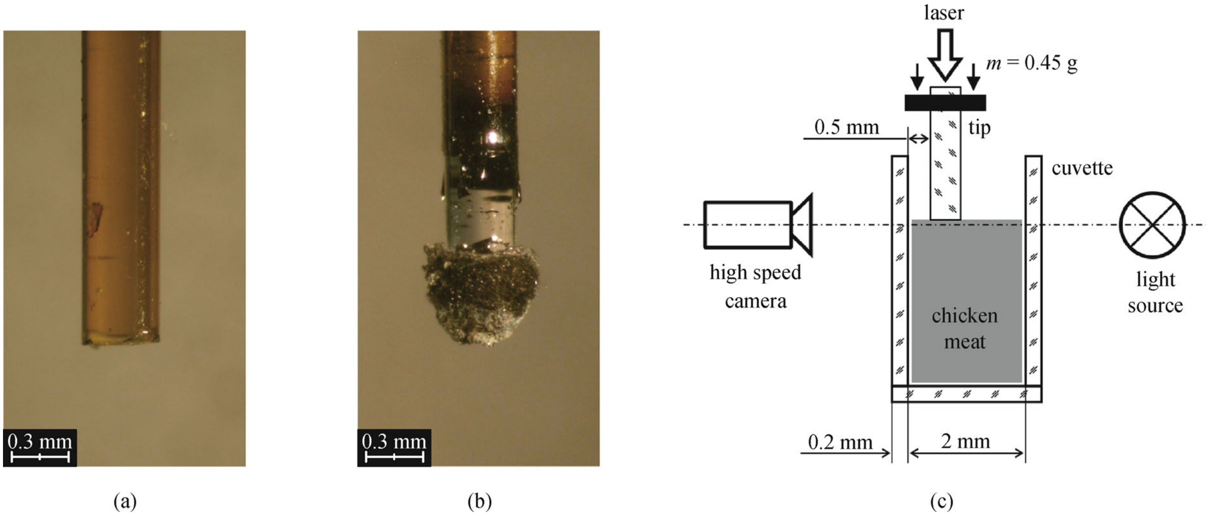
In this study, *in vitro* treatments of soft tissue by laser surgery and hot-tip surgery at a wavelength of (980 ± 10) nm were monitored by a high-speed video camera. Chicken meat was exposed to continuous wave (CW) and pulsed laser modes with the same average power but different peak pulse powers. The depth and width of the damage area around the crater of tissue wounds formed by the two laser modes were measured. We used four treatment regimes as follows: 1) continuous clear-tip action (laser surgery, CW mode) with an average power of 10 W; 2) pulsed clear-tip action (laser surgery, pulsed mode) with an average power of 10 W and peak power of 20 W; 3) continuous hot-tip action (hot-tip surgery, CW mode) with an average power of 10 W; and 4) pulsed hot-tip action (hot-tip surgery, pulsed mode) with an average power of 10 W and peak power of 20 W. The influence of pulsed diode laser power at a wavelength of (980 ± 10) nm on wounds induced by laser surgery and hot-tip surgery with the same average laser power was also evaluated.

2 Materials and methods

A diode laser (Alta-ST, Dental Photonics, Inc., Walpole, MA, USA) with a wavelength of $\lambda = (980 \pm 10)$ nm was used in this study; this laser system can be operated in both CW and pulsed modes. The maximum average power of the laser radiation in this study was 10 W, and the maximum pulsed power was 20 W.

Laser radiation was delivered to chicken meat via a quartz-quartz fiber with a core diameter of 320 µm. The distal end of optical fiber was either clear, i.e., formed as a result of a mechanical cleave (clear tip, Fig. 1(a)), or contained an optothermal converter (hot tip, Fig. 1(b)).

The hot tip was formed using the SureStep initiation procedure [21]. This procedure is a computer-controlled multistage process that uses the Alta-ST laser system [21]. SureStep initiation forms a hot tip as a result of irradiation of a unique composite carbon-based target with subsequent



(a) (b) (c)

Fig. 1 Photos of a clear tip (a) and a hot tip (b); scheme of the experimental setup (c) air annealing. Carbon nanoparticles and ions impregnated in the distal end of the quartz fiber form a layer of high-light-absorbing composite material.

Before treatment, chicken meat was sliced by sharp blades (Microtome blade High Profile; Feather Safety Razor Co., Japan) to a thickness of (2.0 ± 0.1) mm, width of (40.0 ± 0.5) mm, and height of (7.0 ± 0.1) mm. Each slice was then placed in a glass cuvette with inner space dimensions of (2.0 ± 0.1) mm × (45.0 ± 0.1) mm × (10.0 ± 0.1) mm. The thickness of the glass cuvette wall was (0.20 ± 0.01) mm (Fisher Scientific; USA). This glass cuvette had one open side, a length of (2.0 ± 0.1) mm, and a width of (45.0 ± 0.1) mm. The soft tissue was placed in the cuvette so that one of the tissue surfaces was within 2 – 3 mm from the open entrance, and another surface was set against the cuvette bottom (Fig. 1 (c)). The cuvette with tissue was placed between the light source (Schott DCR III; Mexico) and the objective of the high-speed video camera (Photron FASTCAM SA4, Japan) so that the video camera axis was transverse to the optical fiber axis.

During lasing, the clear tip (Fig. 1(a)) or hot tip (Fig. 1 (b)) was pressed down against the outside surface of the soft tissue. The vertical loading force was (0.45 ± 0.01) g for both cases. The distance from the side of the tip to the inner wall of the glass cuvette directed to the camera was (0.5 ± 0.1) mm. The tip could move freely along its axis, and no lateral movement of the tip along the tissue surface was performed.

The laser was operated in CW (continuous emission) mode with an average power of 10 W (12.4 kW/cm^2) and pulsed (pulsed emission) mode with an average power (P_a) of 10 W and peak power (P_p) of 20 W (24.8 kW/cm^2). In pulsed mode, pulses with duration $\tau_p = 25$ μs and repetition rate $F = 20$ kHz were applied. Pulsed mode was generated by modulating the diode pump current.

In each experiment, we recorded a high-speed video of events in the tissue surrounding of the tip during and after laser treatment. The recording was performed at a rate of 2000 frames/s; thus, the exposure time of one frame was 1/2000 s. Recording began simultaneously with the start of lasing. The recording duration was 5 s, and the lasing duration was 3.5 s.

Lasing was performed using a clear tip (laser surgery) or hot tip (hot tip surgery) on 10 fragments of soft tissue for each method. High-speed video data were recorded and analyzed. The events occurring in tissue caused by lasing were observed. The time interval from the beginning of lasing to each tissue event was determined, and the crater depth and width of collateral damage in soft tissues were measured immediately after laser action.

Statistical processing of the data was performed using the software package StatGraphics Plus 2.1 (USA).

3 Results and discussion

Results of the interaction between the diode laser at a wavelength of (980 ± 10) nm and the chicken meat during laser surgery are presented in Fig. 2. Figures 2(a) and 2(b) respectively show the temporal evolution of soft tissue during laser surgery in CW and pulsed modes.

During both laser surgery and hot-tip surgery, soft tissue first coagulated, subsequently became carbonized, and then was finally removed. In our experiments, coagulation was characterized by whitening around the surgery area, which can be caused by changes in the scattering property in the tissue. A dark layer in the soft tissue was considered as carbonization, which can result from formation of carbon particles by decomposition of biological tissue during surgery. Tissue cutting occurred as the tip moved deeper into the tissue, thereby increasing the crater depth.

At 200 ms after laser irradiation, coagulation was

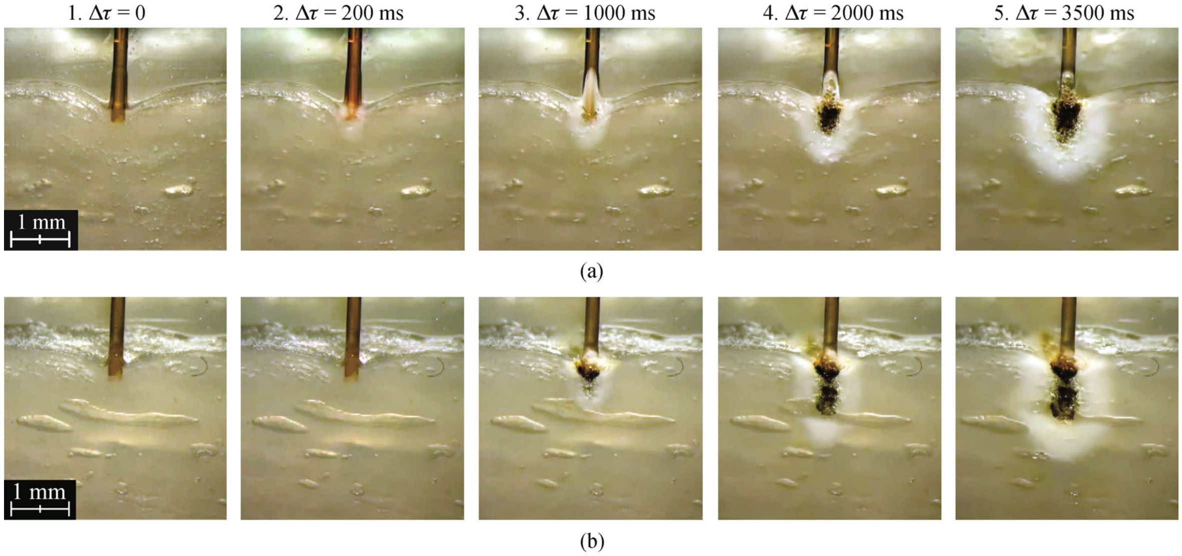


Fig. 2 Temporal evolution of soft tissue before and after laser surgery in CW mode (a) and pulsed mode (b)

apparent in CW mode but absent in pulsed mode. After 1000 ms, carbonization was visible at pulsed mode but absent in CW mode. At 2000 and 3500 ms, coagulation, carbonization, and cutting appeared for both modes of laser surgery, but the crater depth and width of collateral damage achieved by the pulsed mode laser were higher than those achieved by the CW mode laser.

Results of the interaction between the diode laser at a wavelength of (980 ± 10) nm and chicken meat during hot-tip surgery are presented in Fig. 3. Figures 3(a) and 3 (b) respectively show typical results of the temporal evolution of soft tissue during hot tip surgery in CW and the pulsed modes.

During hot-tip surgery, coagulation and carbonization were visible in both CW mode and pulsed mode about 200 ms after laser irradiation. After 1000, 2000, and 3500 ms, no significant differences in crater depths and widths of collateral damage were observed between CW mode and pulsed mode.

Tissue morphologies obtained after lasing by the two modes are shown in Figs. 4 and 5. Figures 4(a) and 4(b) respectively show the tissue morphologies obtained after laser surgery in CW and pulsed modes. Figures 5(a) and 5 (b) respectively show the tissue morphologies obtained after hot-tip surgery in CW and pulsed modes.

Figure 6 shows the analysis results of the influence of laser operation mode (CW vs. pulsed) and type of surgery (laser vs. hot-tip surgery) on crater depth (h_r) and collateral damage width (h_c) in the tissue after 3.5 s of lasing.

Figure 7 shows the analysis results of the influence of lasing mode and type of surgery on the duration from the start of lasing to coagulation (t_c), carbonization (t_{carb}), and removal (t_r) of biological tissue.

As shown in Fig. 6(a), crater depths (h_r) of (1.1 ± 0.1) and (1.8 ± 0.2) mm were achieved during laser surgery in CW mode and pulsed mode, respectively. In addition, h_r of (3.7 ± 0.4) and (3.6 ± 0.4) mm were also obtained during hot-tip surgery in CW mode and pulsed mode, respec-

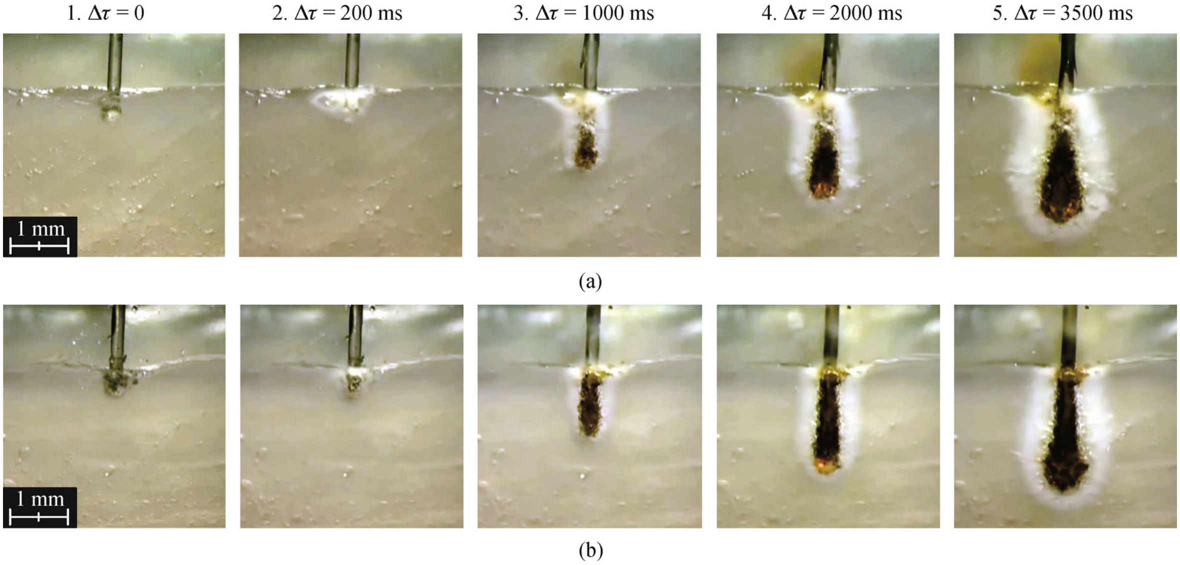
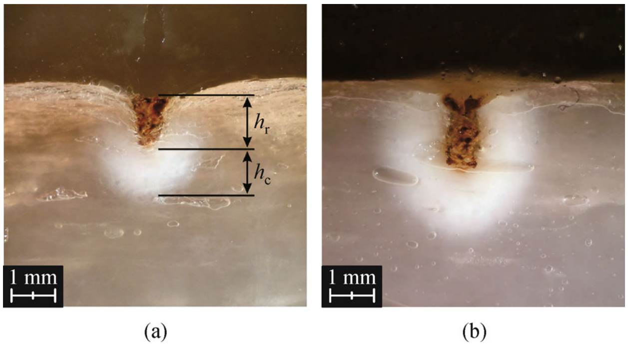
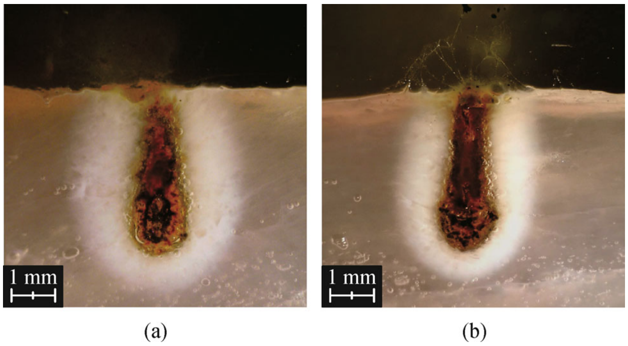


Fig. 3 Temporal evolution of soft tissue before and after the start of hot tip surgery in CW mode (a) and pulsed mode (b)



(a) (b)

Fig. 4 Soft tissue morphologies after laser surgery in CW mode (a) and pulsed mode (b). h_r: crater depth; h_c: collateral damage width



(a) (b)

Fig. 5 Soft tissue morphologies after hot tip surgery in CW mode (a) and in pulsed mode (b)

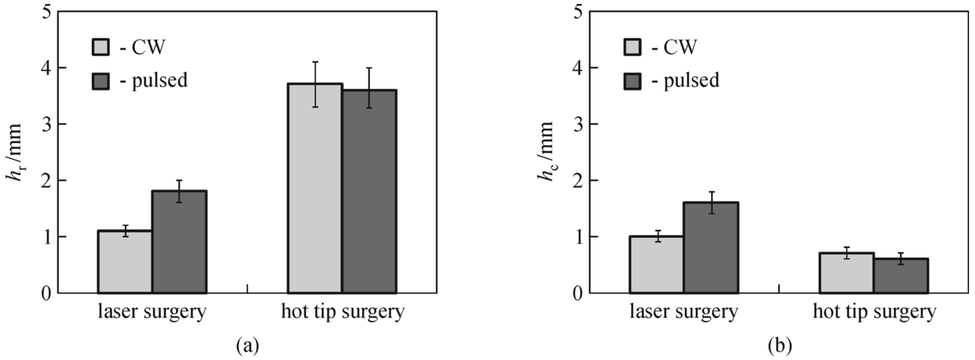


Fig. 6 Crater depth h_r (a) and collateral damage width h_c (b) in chicken meat (error bars show confidence interval)

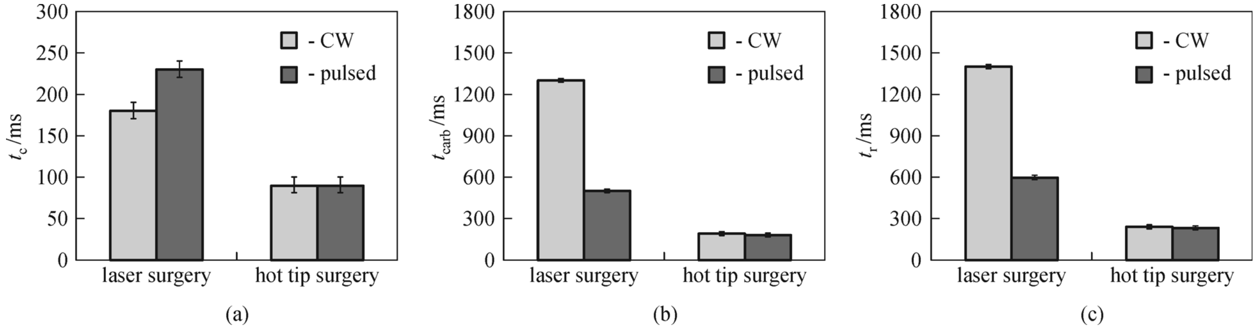


Fig. 7 Duration from the start of lasing to coagulation t_c (a); carbonization t_{carb} (b); and removal t_r (c) of chicken meat (error bars show confidence interval)

tively. Significant differences in h_r were not detected between the two laser modes during both laser and hot-tip surgery.

As shown in Fig. 6(b), the collateral damage width (h_c) of soft tissue measured (0.7 ± 0.1) mm during hot-tip surgery in CW mode and (0.6 ± 0.1) mm during surgery in pulsed mode. Here, the values of h_c during hot-tip surgery were 1.4–2.7 times smaller than those observed during laser surgery in these two modes.

The h_c formed during laser surgery in pulsed mode was larger than that observed during surgery in CW because coagulation of biological tissue begins later in pulsed mode than in CW mode. According to Fig. 7(a), coagulation of tissue began (230 ± 10) ms after the start of lasing in pulsed mode and (180 ± 10) ms after the start of lasing in CW mode. These results may be attributed to the compensation of higher tissue temperatures attributed to increases in peak power during pulsed-mode lasing by cooling of the tissue between laser-pulse intervals. Carbonization and tissue removal began earlier during laser surgery in pulsed mode than in CW mode (Figs. 7(b) and 7(c)). Figure 7(b) shows that during laser surgery, carbonization begins (500 ± 10) ms after the start of lasing in pulsed mode and (1300 ± 10) ms after the start of lasing in CW mode. Figure 7(c) shows that tissue removal (i.e., tissue cutting) begins (600 ± 10) ms after the start of lasing in pulsed mode and (1400 ± 10) ms after the start of lasing in CW mode. These results may be explained by the greater peak power in pulsed mode inducing more carbon particles to form in the surgical area.

Increasing the peak power up to 20 W while maintaining the average power at 10 W during hot-tip laser surgery did not result in significant differences in crater depth and collateral damage width. This result may be explained by the observation that coagulation, carbonization, and tissue removal occur nearly simultaneously during hot-tip surgery in pulsed mode or CW mode. Coagulation occurred at (90 ± 10) ms (Fig.7(a)) in both modes, and carbonization began at (180 ± 10) ms in pulsed mode and at (190 ± 10) ms in CW mode (Fig.7(b)). Removal also began at (230 ± 10) ms after the start of lasing in pulsed mode and (240 ± 10) ms after in the start of lasing in CW mode (Fig.7(c)).

The use of an optothermal converter during hot-tip laser surgery increased the crater depth and reduced the width of collateral damage in soft tissue at the same average laser power ($P_a = 10$ W). Therefore, the average efficiency of laser energy conversion into heat during hot-tip surgery is higher than that during the laser surgery. As shown in Fig. 7(a), coagulation by the hot tip began 2.0–2.5 times earlier than that by the clear tip. Furthermore, as shown in Fig. 7 (b), carbonization by the hot tip began approximately 2.7–

6.8 times earlier than that by the clear tip. This difference in efficiency may be caused by the different dynamics of laser radiation absorption of the tips. Absorption of the hot tip is constant during lasing and depends on the absorption coefficient of the material of the hot tip. Absorption of the clear tip is minimal at the beginning of lasing and corresponds to the soft tissue absorption coefficient at the wavelength of laser radiation. Absorption of the tip increases when carbonization forms on the surfaces of the tissue wound and tip. Formation of the carbonization layer enhances absorption in the tissue treatment area because the absorption coefficient of carbon (1000 cm^{-1} at 980 nm [35]) is much greater than that of the soft tissue [25] at 980 nm.

4 Conclusions

Comparison of laser and hot-tip surgery of chicken soft tissue in CW and pulsed modes was achieved by high-speed video recording. When the laser mode was changed from CW mode to pulsed mode during laser surgery, an increase in crater depths and areas of collateral damage width were observed in the tissue. Tissue coagulation began later and carbonization and cutting occurred earlier during laser surgery in pulsed mode than during surgery in CW mode. Switching from CW mode laser to pulsed mode during hot tip surgery did not result in significant differences in the crater depth and width of collateral damage in the tissue. Coagulation, carbonization, and tissue removal began earlier during hot-tip surgery than during laser surgery. At the same average laser power (P_a = 10 W), use of the hot tip instead of the clear tip increased the crater depth and reduced the width of collateral damage formed in the soft tissue.

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