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Comparison of Laser-Induced Damage With Forward-Firing and Diffusing Optical Fiber During Laser-Assisted Lipoplasty

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Abstract

Background and Objectives—Laser-assisted lipoplasty is made possible by using an optical fiber that delivers light endoscopically to subcutaneous fat tissue. Most optical fibers for laser-assisted lipoplasty are designed to be irradiated in a forward direction. In this study, we compared forward-firing fiber and diffusing fiber for use in laser-assisted lipoplasty. The effective parameters of the ablation pattern which resulted from the laser-induced damage are discussed for both systems. In particular, we note the effect resulting from the different beam emission patterns and the contours of laser fluence.

Methods—We used two different laser delivery systems (a forward-firing fiber and a diffusing fiber) to examine how the beam emission pattern affects the laser-assisted coagulation and damage pattern of in vitro fat tissues. A porcine liver tissue (water-rich tissue) was used as a secondary laser target to investigate how the laser-assisted coagulation pattern depends on both the type of tissue (water-rich and lipid-rich tissue) as well as the delivery system. An evaluation using a digital camera and a thermal camera was conducted for the tissue ablation processes in order to observe the generated heat transfer in fat and liver.

Results—The overall shape of the laser-assisted coagulation zone was different from the beam emission pattern in the case where a forward-firing fiber was used within fat tissue. The center of the laser-affected zone is characterized by the formation of a reservoir of melted fat. In the thermal image analysis, there existed a discrepancy between the temperature distribution of the fat tissue and the liver tissue during the forward-firing fiber irradiation. In the liver tissue ablation process, the temperature distribution during the laser ablation also demonstrated an elongated ellipse that matches well with the laser-induced damage zone. The temperature distribution in fat tissue adhered to a more discoid pattern that corresponded to the laser-induced damage zone.

Conclusions—Based on our findings, we have proposed mechanisms that can explain the laser-induced damage in both tissues when a forward firing fiber is employed as the delivery system. In the case of fat tissue, the ablation mechanism can be characterized by the reservoir formation of melted lipids while the ablation is characterized as the well-known drilling effect for liver tissue.

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Keywords

laser-induced damage; fiber optics; lipoplasty; endoscopy surgery

INTRODUCTION

Lipoplasty refers to cosmetic surgery that uses various methods to remove unnecessary fat from the human body for cosmetic reasons. Laser-assisted lipoplasty has been widely used since the first trial of laser-assisted fat removal using the Nd:YAG laser in the 1990s [1,2]. Laser-assisted lipoplasty is performed by endoscopic irradiation of various laser sources into the subcutaneous fat tissue. The application of laser light into the human body is made possible by an optical fiber that delivers light endoscopically to the subcutaneous fat tissue. Current optical fibers for laser-assisted lipoplasty are designed to be forward firing [3–8]: the light exits the distal end of the fiber along the optical axis.

In some applications of laser-assisted surgery, it is necessary to change the direction and distribution of the light emission at the distal end of the optical fiber. A diffusing fiber tip is often employed and proposed for various endoscopic surgeries including photo-dynamic therapy laser, laser lipoplasty, and laser surgery [9–12]. Due to scattering around the distal end, the light-emitting pattern of the diffusing fiber exhibits a uniform distribution along the distal end. The even distribution of laser light leads to a broad and uniform outcome near the distal end.

A potentially promising issue to investigate might be how reconfiguring the optical fiber end to produce a diffusing output affects the ablation mechanism in comparison to a forward firing configuration. To the best of our knowledge, no previous study has examined the discrepancy of laser-induced ablation between a forward firing and a diffusing fiber during the laser-lipoplasty.

In this study, laser-assisted coagulation and damage patterns using forward and diffusing fiber were compared by irradiating a continuous wave infrared (IR) laser into subcutaneous porcine fat. We compared our observations of the laser-induced damage and discussed the impacting factors upon the resultant laser ablation patterns. Special note was taken of the effects created by the different beam emission patterns and the contours of laser fluence. A secondary laser target tissue (porcine liver) was used to better understand how the laser-assisted coagulation and damage pattern depends on the type of tissue (lipid-rich fat tissue and water-rich liver tissue).

MATERIALS AND METHODS

Since the FDA approval in 2006, the Nd:YAG laser has become one of the most widely used laser source for the laser-assisted lipoplasty [13–16]. We employed a diode-pumped solid state (DPSS) Nd:YAG laser as the irradiating source for laser lipoplasty. This laser produces continuous wave light at a wavelength of 1,064 nm and a maximum power of 20 W. A low OH-optical fiber was used to deliver the 1,064 nm light into soft tissues. The core diameter of the fiber is 600 μm with a clad diameter of 660 μm and an outer diameter of 710 μm (FIP

600660710, Laser Component, GmbH). Two different laser delivery systems (a forward-firing fiber and a diffusing fiber), were used in the current study. In the forward-firing case, the polyimide buffer was stripped and the tip of the low OH-fiber was cleaved. Once the fiber was cleaved, the optical fiber was cleaned with cleaning paper and acetone. In the case of diffusing emission, we used a homemade diffusing fiber by modifying the distal end of the forward-firing fiber. The manufacturing process used to produce the diffusing fiber is shown in Figure 1.

The scattering medium (aluminum oxide powder with a particle diameter of 10 μm) and ultraviolet (UV) curable resin were mixed in a weight ratio of 1:30 (Fig. 1a). Once the powder and the resin were mixed, the resin was injected gently into a glass cylindrical tube (a capping tube) with an inner diameter of 2 mm using a syringe (Fig. 1b). A vacuum desiccator was used to remove air bubbles inside the resin (Fig. 1c and d). The tip of the low OH-fiber was cleaved in the same way as the forward-firing fiber. The optical fiber tip was then inserted into a glass tube that was filled with aluminum oxide powder and resin. An UV lamp with a power of 20 W was used to cure the resin for 20 seconds (Fig. 1e).

Photographic imaging of visible light delivery has been used to evaluate the emission profiles of optical fibers [17]. The beam emission patterns were examined using a digital camera after coupling a He:Ne laser into the proximal end of both forward and diffusing fiber. The distal ends of the fiber were positioned flat on white paper. Images of the reflected light from the paper were captured with a digital camera. The images were taken in a dark room (Fig. 2).

For the laser ablation process, the distribution of laser fluence inside both tissue types for the forward-firing fiber was evaluated with the Monte-Carlo method to examine the resultant effects [18]. The optical properties of the tissues are taken from literature [19–24].

Fresh porcine fat tissues from the back-bone and liver tissue were obtained from a local slaughterhouse. Samples were cut into pieces about 5 cm (width) $\times$ 5 cm (length) $\times$ 3 cm (height) and kept at room temperature. The samples were then placed on a 3-cm-thick insulating stage prior to laser irradiation. The insulating stage was used to prevent heat loss from the bottom of the sample. Guiding needles were used to steer the irradiation fiber tip within the tissue samples. An 18 gauge stainless needle was used for the forward firing fiber. A custom-made guiding needle with an inner diameter of 3 mm was used for the diffusing fiber. The guiding needle was inserted into the tissue samples 3 cm below the surface. Once the guiding needle was located at its target destination, the optical fibers were threaded into the tissue through the needle until the fiber tips reached the end of the needle. The guiding needle was then completely retracted from the sample tissues in order to avoid dissipation of heat through it. Once the guiding needle was removed, the laser light was irradiated into the tissue. The proximal end of the fiber was connected to a continuous wave DPSS laser with a wavelength of 1,064 nm, and laser light was delivered into the interior of the tissue sample (Fig. 3a). Four laser power and duration cohorts were tested (1 minute irradiation at a laser power of 15 W, 2 minutes irradiation at 15 W, 1 minute irradiation at 20 W, and 2 minutes irradiation at 20 W). A least three samples were irradiated for each laser cohort and each fiber type. After laser irradiation, the guiding needle was re-inserted into the tissue and the

fiber tip was carefully removed. The laser-affected zones inside the samples were imaged and examined using a digital camera after dissecting the laser-induced damage zone with a surgical scalpel. The dimensions (length and width) of the laser-induced damage zones were estimated based on the digital camera images for all laser power cohorts and two fiber tips. The estimates were conducted through a blind test by five individuals with no knowledge of the fiber type and laser parameters. The length is defined as the axial extension of the damage zone with respect to the direction of fiber alignment. The width is defined as the lateral extension of the damage zone with respect to the direction of fiber alignment.

In order to clarify the boundary of the laser-affected zone in fat tissue, laser-irradiated fat tissue was stained with nitro blue tetrazolium chloride (NBTC) [20]. First, the fat tissue was fixed for 10 minutes with a 4% paraformaldehyde solution. The tissue was then washed twice for 10 minutes with a phosphate-buffered saline solution. After the fixing and washing, the fat tissue was immersed for 12 hours in NBTC staining solution. The laser-induced damage zone appears white (non-stained) and the non-damaged zone appears blue (stained with NBTC). The images of stained fat tissue were taken using a digital camera, and the laser-induced damage zone was estimated with the aforementioned blind test.

To examine how fiber insertion affected the laser-affected zone, laser light was irradiated onto the target tissue without inserting the fiber tip into the tissue. The tip of the forward-firing fiber was placed vertically on the surface of the fat and liver tissue (Fig. 3b). Irradiation for 10 minutes at 10 W of power and 5 minutes at 5 W of power was applied to the fat tissue and liver tissue, respectively. The irradiated region was dissected along the axial direction of the irradiation fiber with a surgical scalpel to observe the coagulation region. Images were taken using a digital camera.

We employed a thermal IR camera (A320 FLIR) to monitor the laser-induced temperature rise within tissue in order to correlate the temperature rise and thermal damage. The tips of the forward-firing fiber and the diffusing fiber were placed horizontally on the surface of the fat and liver tissue. A glass plate of 0.7 mm thickness was located in contact on top of the soft tissues and optical fiber. Since the glass plate was very thin and in direct contact with the tissue, the heat of the laser-assisted damage zone was conducted through the glass. The temperature of the glass plate and laser-assisted damage zone were expected to be similar. This was confirmed by experiment with a sample plate. When the glass plate was located on the preheated plate, the temperature difference between the plated and the glass was measured to be less than 5 °C. The laser produced continuous wave light at a wavelength of 1,064 nm for 8 minutes at 7 W of power and it was applied to the fat and liver tissue by the two different laser delivery systems. During the light irradiation, we were able to obtain and monitor the thermal images at 30 frames per second using a thermal camera. The laser-induced temperature elevation and heat distribution around the fiber tip were examined by thermal image analysis (Fig. 3c).

RESULTS

The beam emission patterns of the forward-firing fiber and the diffusing fiber are compared in Figure 2. The emission from the forward-firing fiber clearly demonstrates a one-

directional emission. In contrast to the forward-firing fiber, the emission profile from the homemade diffusing fiber shows a scattering emission at the tip of the fiber. The scattering medium caused the beam to diffuse around the fiber tip, and the overall shape of the emission has a cylindrical core and an elliptical distribution around the capping tube.

The distribution of laser fluence for the forward firing fiber is shown in Figure 4. The optical parameters of the tissue used were a reflective index (fat: 1.46, liver: 1.5), an absorption coefficient (fat: 0.06 cm^{-1} , liver: 0.08 cm^{-1}), a scattering coefficient (fat: 136 cm^{-1} , liver: 202 cm^{-1}), and an anisotropic factor (fat: 0.90, liver: 0.95). Since accurate data for the optical parameters of fat tissue at 1,064 nm wavelength is not available, the parameters used were assumed based upon various references [19–24]. Regardless of the tissue type, the high fluence area was located within a 1-mm distance of the fiber's distal end. Within this area, the fluence of laser power was observed to decrease by about 50% at 0.5 mm. At a 1-mm distance, it was reduced by about 70%. The overall shape of the high fluence area was an elongated ellipse while the low fluence area had a circular shape due to scattering.

The laser-induced damage of fat tissues was examined without staining and with NBTC staining. Images of the laser-affected zone are shown in Figure 5. The actual location of the fiber tip and the capping tube of the diffusing fiber are displayed with imaginary lines (a solid line for the fiber tip and an alternate long and short dash line for the capping tube). The boundary between the laser-affected zone and non-affected zone is more clearly visible in the NBTC-stained images. The non-affected zone was stained blue and the laser-affected zone was not stained. The boundary between the two regimes is represented with an imaginary line (elliptical dotted line) in the NBTC staining images. In the case of the forward-firing fiber (Fig. 5a and b), it is clear that the laser-affected zone can be divided into two distinct regions. The center of the laser-affected zone (where the distal end of the fiber is located) is characterized by melting of the fat tissue and the formation of a reservoir of melted fat. The reservoirs were bigger and more clearly observed with the high-power irradiation and longer irradiation time. The reservoirs were surrounded with a laser-induced thermal coagulation zone. The laser-induced thermal coagulation zone appears slightly darker in the non-stained images and appears brighter in the NBTC-stained images. It should be noted that the overall shape of the laser-assisted coagulation zone does not match the beam emission pattern of the forward-firing fiber. The coagulation pattern is an elliptical shape while the emission pattern resembles elongated pattern. We noted that the tip of the fiber is located at the center of the laser-assisted coagulation zone.

In the case of the diffusing fiber (Fig. 5c and d), the melting and formation of a reservoir were not observed for all of the conditions tested. However, the laser-induced thermal coagulation zone was clearly distinguished from the non-damaged zone. The coagulation zone formed an elliptically around capping tube. In contrast to the forward firing case, the shape of the laser-assisted coagulation zone resembles the beam emission pattern of the diffusing fiber.

The dimensions of the laser-assisted coagulation zone were measured from the digital camera images. The widths, lengths and aspect ratio of the coagulation zones are shown in Figure 6 for all tested conditions and for two different fibers. The lengths and widths of the

laser-assisted coagulation zones increased with increasing laser power and irradiation time, regardless of the fiber type. The widths of the coagulation zones for the two fiber types were almost identical for all tested conditions (Fig. 6a). The length of coagulation with a forward-firing fiber was larger than the length with a diffusing fiber (Fig. 6b). The aspect ratio (the width divided by the length) of the coagulation zone was evaluated in order to quantitatively compare the shape of the coagulation region. The aspect ratio of the diffusing fiber was larger than that of forward firing fiber by 11–24% (Fig. 6c).

A porcine liver tissue (water-rich tissue) was used as a secondary laser target to investigate how the laser-assisted coagulation pattern depends on both the type of tissue (water-rich and lipid-rich tissue) as well as the delivery system. Typical cross-section images of the laser-affected zone inside the liver are shown in Figure 7. The laser-affected zone in the liver tissue was observed to be different from the laser-affected zone in the fat tissue. In the case of the forward-firing fiber, the damaged region formed an elongated ellipse that can be divided into two distinct areas. The center of the heat-affected zone is characterized as a laser-induced cavity. A dark carbonized region was created around the cavity, and the bright color of the coagulated region was generated around the carbonized region. The laser-induced carbonization zone resembles the beam emission pattern of the forward-firing fiber.

In the case of the diffusing fiber, a carbonized region was observed only when the laser was irradiated for 2 minutes at a power of 20 W. For all the laser parameters used, the diffusing fiber produced a coagulation zone with an elliptical shape similar to the beam distribution pattern of the diffusing fiber.

The length and width of the carbonized cavity and the coagulation zone increased with increasing laser power and irradiation time, regardless of fiber type (Fig. 8b). The widths of coagulation using the two fiber types were similar for all conditions tested. The length of coagulation with the forward-firing fiber was about 37% larger than the length with the diffusing fiber (Fig. 8a). The aspect ratio of the diffusing fiber was larger than that of forward-firing fiber by 36–65.4% (Fig. 8c).

To examine how fiber insertion affected the laser-affected zone, laser light was vertically irradiated onto the target tissue without inserting the forward firing fiber tip into the tissue. During the fat tissue experiment, we observed that the meltdown of the fat tissue began from the laser-irradiated area. In the cross-sectional shape of the fat tissue, a semicircular-shaped reservoir of melted fat was formed. The reservoir was filled with melted fat, and a white-colored region of coagulation was observed around the reservoir. The boundary between the two regimes is represented with an imaginary line (dotted line) (Fig. 9a). A very thin layer of carbonization was observed in the contact area between the tissue and the fiber. In the liver tissue, a shape was observed similar to the shape that occurred when the laser was irradiated inside the tissue. A tunnel-shaped cavity formed along the direction of the laser beam, and a dark carbonized region was created around the cavity. A region of bright color, indicative of thermal coagulation, was generated around the carbonized region (Fig. 9b).

Evaluations using a digital camera and a thermal camera were conducted for the tissue ablation processes in order to observe the generated heat transfer in fat and liver. Each image

was obtained after 8 minutes irradiation of 7 W by both cameras. The temperature of the laser-induced region was measured by the thermal camera. The laser light delivery, the expansion of ablation region and the generated heat distribution are shown in Figures 10 and 11.

In the thermal image analysis of fat tissue, the maximum temperature was approximately 150°C for the forward-firing fiber case. For the diffusing fiber, the maximum temperature was about 95 °C. The heated region spread outward from the fiber tip and it had a rotund oval shape (Fig. 10). When liver tissue was used, the maximum temperature was approximately 240 °C and the heated region took on an elongated elliptical shape (Fig. 11b). With the diffusing fiber, the maximum temperature was again approximately 95 °C and the damaged region again emanated from the diffusing fiber tip into a rotund oval shape. Regardless of the tissue type, the temperature rise of the forward-firing fiber was higher than that of the diffusing fiber due to the laser power density. The variation in laser fluence arises from the smaller exit area of the forward-firing fiber than that of the diffusing fiber. As a result, the laser fluence of the forward-firing fiber is higher than that of the diffuse fiber given the same laser power condition.

When the forward-firing fiber was used with liver tissue, exhaust smoke was observed which in turn vented back along the optical fiber and created a tail structure.

DISCUSSION

The laser ablation process is quite complicated and its outcome depends on multiple parameters, including the properties of the tissue and the configuration of the laser. In addition, the contour of laser fluence and the laser beam emission pattern affects the laser ablation mechanism. We used two different laser delivery systems (a forward-firing fiber and a diffusing fiber) to examine how the beam emission pattern and the contour of laser fluence affected the laser-assisted coagulation and damage pattern of in vitro fat tissues.

A continuous IR laser was delivered into subcutaneous porcine fat by the two systems. In the case of the forward-firing fiber, the center of the laser-affected zone is characterized by melting of the fat tissue and the formation of a reservoir of melted fat. The reservoirs are surrounded by a laser-induced thermal coagulation zone with a rotund oval shape. We note that the overall shape of the laser-assisted coagulation zone rotund oval shape does not match the beam emission pattern of the forward-firing fiber. The discrepancy between the beam emission pattern and coagulation zone pattern indicates that the laser-affected zone in the fat tissue is not solely governed by the beam emission pattern of the forward firing fiber. In contrast to the forward firing case, melting fat and the formation of a reservoir were not observed in the case of the diffusing fiber due to the lower laser fluence. The coagulation zone formed rotund oval shape around the capping tube of the delivery fiber. Porcine liver tissue was used as a secondary laser target to investigate how the laser-assisted coagulation and damage pattern depends on the type of tissue in addition to the delivery system used. Unlike the lipid-rich fat tissue, the major component of liver is water; 80% by volume [19]. In terms of the optical properties, both tissue types have similar absorption coefficients (μ_a) and the scattering coefficients (μ_s). In the near IR wavelength (789–1,064 nm), the

absorption coefficients (μ_a) were found to range from 0.06 to 0.08 cm^{-1} and the scattering coefficients (μ_s) were found to range from 10.1 to 13.6 cm^{-1} [22–24]. In determination of the thermal properties, the heat diffusion rate of the fat tissue and liver tissue were 0.173 and 0.107 $\text{mm}^2/\text{second}$, respectively. Because both tissue types have a similar absorption coefficient (μ_a) and thermal diffusion rate (α), the thermal diffusion times (t_d) of both tissues were similar [19–20,22–24].

The laser-affected zone inside the liver tissue was found to be different than the fat tissue. In case of the forwardfiring fiber, the center of the heat-affected zone is characterized as a laser-induced carbonized cavity, and the coagulated region was generated around the carbonized cavity.

We note that the laser-assisted carbonization zone and coagulation zone bear an obvious resemblance to the beam emission pattern of the forward-firing fiber. The aspect ratio of coagulation zone is approximately 30% lower than that of fat tissue. The low aspect ratio indicates that the laser-assisted coagulation zone has an elongated shape along the laser irradiation direction. In the case of the diffusing fiber, laser irradiation produced a coagulation zone with an elliptical shape similar to the beam distribution pattern of the diffusing fiber. Among the four tested cases, the overall shape of the laser-assisted damage zone were similar in the beam emission pattern for three cases; diffusing fiber in fat, diffusing fiber in liver and forward firing fiber in liver. However, the overall shape of the laser-assisted coagulation zone was different in the beam emission pattern for the case of fat tissue with a forward firing fiber. In the contour of laser fluence simulation for the forward-firing fiber, the laser-assisted damage pattern was different from the distribution pattern of the laser fluence. Regardless of the tissue type, the primary laser fluence distribution was localized at the front of the fiber's distal end but the damage pattern was extended beyond the primary laser fluence contour. In the case of liver tissue with the forward-firing fiber, the laser-assisted damage zone was observed in front of the fiber distal end as well as at a relatively long distance from the fiber tip. In the case of fat tissue with the forward-firing fiber, the damage pattern was observed in front of the fiber distal end and behind the fiber tip.

Proposed mechanisms that can provide a possible explanation for induced effects in the cases of the forward firing fiber in both liver and fat as well as for the diffusing fiber in both tissues. In the case of the forward-firing fiber in liver, the ablation mechanism can be characterized as the well-known drilling effect [25] which is illustrated in Figure 12. Upon the irradiation of laser light into liver tissue, the light starts to be absorbed from the tip of the fiber.

The resultant temperature of the laser-irradiated region increases rapidly. According to our IR camera observation, it was measured that the temperature of the tissue near the fiber tip rose to the water vaporization temperature (100 C at standard pressure) within a few seconds. Once the temperature reached the vaporization temperature, the continuing laser irradiation lead to the dehydration and removal of tissue near the distal end of the fiber. The adjacent tissue layer was then exposed to the continuing laser irradiation and was heated up. The heated adjacent layer was removed and the ablation front moved deeper and deeper into

the tissue. This layer by layer ablation resulted in the laser-induced drilling of tissue. While the tissue was continuously drilled, the wall of the drilled zone got carbonized and a zone of coagulated collateral damage formed around the drilled wall. The drilled channel and the collateral damage zone usually took the form of an elongated elliptical shape. The temperature distribution during the laser ablation process (Fig. 11) also demonstrated an elongated ellipse that matches well with the laser-induced damage zone in Figure 7. The continuous drilling effect in liver was also confirmed with the secondary ablation measurement in which the laser light was irradiated onto the surface of the liver tissue instead of being irradiated inside the tissue (Fig. 9).

In contrast to water-rich liver tissue, fat tissue is in a solid state at room temperature and melts within a temperature range from 30 to 50 C. The onset of tissue damage in porcine fat tissue occurs from its smoke point which is approximately 200 C. The smoke point of fat tissue is about two times higher than the vaporization temperature of water at standard pressure. We propose a mechanism that can explain the laser-induced damage in fat tissue with a forward firing fiber. The proposed mechanism is characterized by the reservoir formation by melted lipids and is shown in Figure 13. When the light is irradiated into fat tissue, the light started to be absorbed from the tip of the fiber as was also observed in the liver case. The temperature of the laser-irradiated region started to rise and reached the melting point of fat. This resulted in the initiation of a small reservoir of melted lipids near the fiber tip. The temperature of the melted lipids kept increasing beyond the melting point; however, the temperature of the reservoir did not reach the smoke point of fat. The continuous irradiation of light leads to more melting and an expanded reservoir. The liquid phase fat could not escape out of the laser-irradiated zone and was trapped in the reservoir. The trapped liquid phase fat then absorbed the laser light and hindered the light from reaching the opposite side of the reservoir. Because of this shielding by liquid fat, the laser light was not able to “drill” the fat tissue beyond a certain dimension and thus produced a melting zone with a high aspect ratio in comparison to within the liver tissue. The absorption of light by the liquid-phase fat also lead to thermal conduction and coagulation around the reservoir. The observation shown in Figure 9a can also be explained in terms of the proposed reservoir formation of melted fat. We observed that a semi-circular shaped reservoir was formed, and the reservoir was filled with oil in the dissected fat tissue. During continuous laser irradiation, we observed that the fat tissue had liquefied and the resulting reservoir gradually increased in a semi-circular shape. It should be also noted that there existed a discrepancy between the temperature distribution of the fat tissue and the liver tissue during the forward-firing fiber irradiation (Fig. 9). The temperature distribution in liver tissue demonstrates an elongated elliptical pattern while the temperature distribution in fat tissue adhered to a more discoid pattern that corresponded to the laser-induced damage zone in the fat tissue.

Unlike the case of the forward-firing fiber, the diffusing fiber was located in the middle of the laser-assisted coagulation zone after the irradiation. This indicates that the heat generation occurred by the absorption of light around the fiber tip and the thermal energy then transferred to the surrounding area. As a result of this, the laser-induced damage region has a rotund oval shape that resembles the light distribution around the diffusing fiber.

We expected that the uniform distribution from the diffusing fiber could lead to a more volumetric damage zone compared to the forward fiber which is currently used in clinics. However, the diffusing fiber did not produce more melting of fat due to the low fluence and the difference of the aspect ratio in the fat tissue which was about 60% smaller than in the liver tissue. Collateral damage patterns of forward firing fiber and diffusing fiber were very similar. Laser-assisted lipoplasty in clinic is achieved by the laser-induced melting and collateral damage around the irradiated zone. Because of this, laser-induced melting and collateral damage are the two most important parameters that determine the outcome of the laser lipoplasty. Under the experimental conditions of our current study, the diffusing fiber did not have an advantage in the shape and volume of the laser-induced damage. However, even though the fluence is higher, we expect that the corresponding elevation of temperature and subsequent melting will be less using during laser-assisted lipoplasty with a diffusing fiber. Under these conditions, secondary damage, such as burns to the skin should be minimized. By using a diffusing fiber during ablation in liver and similarly other water-rich tissues, carbonization can be significantly reduced and damage to the surrounding tissue can be minimized as a result of forming a circularly shaped coagulation zone.

CONCLUSIONS

In this study, we compared a forward-firing fiber and a diffusing fiber for use in laser-assisted lipoplasty. We discussed the parameters which affected the laser ablation pattern. Our particular focus was on the effects induced by the different beam emission patterns and the contours of laser fluence. In the case of the forward-firing fiber, the center of the laser-affected zone is characterized by melting of the fat tissue and the formation of a reservoir of melted fat. The overall shape of the laser-assisted coagulation zone created by the forward-firing fiber was different from its beam emission pattern. In the case of the diffusing fiber, the melting and formation of a reservoir were not observed in all of the conditions tested. The shape of the laser-assisted coagulation zone resembles the beam emission pattern of the diffusing fiber. In addition to the delivery system used, porcine liver tissue was selected as a secondary laser target to investigate how the laser-induced pattern depends on the type of tissue. In the case of the forward-firing fiber, the center of the heat-affected zone in the liver tissue is characterized as a laser-induced carbonized cavity and the coagulated region was generated around the carbonized cavity. The laser-induced carbonization zone resembles the beam emission pattern of the forward-firing fiber. In the case of the diffusing fiber, laser irradiation produced a coagulation zone with an elliptical shape similar to the beam distribution pattern of the diffusing fiber. The distribution of laser fluence simulation for the forward-firing fiber and the laser-assisted damage pattern were compared. The laser-assisted damage pattern was different from the distribution pattern of laser fluence inside the tissue. The primary laser fluence distribution was localized at the front of the fiber's distal end but the damage pattern was extended beyond the primary laser fluence contour. The final damaged pattern did not match the contour of laser fluence.

An evaluation using a digital camera and a thermal camera was conducted for the tissue ablation processes in order to observe the generated heat transfer in fat and liver. There existed a discrepancy between the temperature distributions of the fat tissue and the liver tissue during the forward-firing fiber irradiation. In the liver tissue ablation process, the

temperature distribution during the laser ablation also demonstrated an elongated ellipse that matches well with the laser-induced damage zone. The temperature distribution in fat tissue adhered to a more discoid pattern that corresponded to the laser-induced damage zone.

Based on our findings, we have proposed mechanisms that can explain the laser-induced damage in both tissues when a forward firing fiber is employed as the delivery system. In the case of fat tissue, the ablation mechanism can be characterized by the reservoir formation of melted lipids while the ablation is characterized as the well-known drilling effect for liver tissue.

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Fig. 1.
Manufacturing process of the scattering diffusing fiber.

Fig. 2.

a: Diffusing fiber tip optical image. **b:** Diffusing fiber beam profile image. **c:** Forward-firing fiber tip optical image. **d:** Forward-firing fiber beam profile image.

Fig. 3.

A schematic illustration of the experimental setup for (a) ablation of the lipid-rich tissue and water-rich tissue into the interiors (b) examining the effects of fiber insertion and (c) examining the extent of the coagulation region and heat distribution as in the soft tissue.

Fig. 4.
The distribution of laser fluence **(a)** inside of the fat tissue and **(b)** liver tissue.

Fig. 5.

Typical coagulation lesions of fat tissues. Before staining (**a–d, i–l**). After staining (**e–h, m–p**). **a** and **e**: Forward-firing fiber, 15 W1 minute. **b** and **f**: Forward-firing fiber, 15 W2 minutes. **c** and **g**: Forward-firing fiber, 20 W1 minute. **d** and **h**: Forward-firing fiber, 20 W2 minutes. **i** and **m**: Diffusing fiber, 15 W1 minute. **j** and **n**: Diffusing fiber, 15 W2 minutes. **k** and **o**: Diffusing fiber, 20 W1 minute. **l** and **p**: Diffusing fiber, 20 W2 minutes (a solid line for the fiber tip, a dotted line for laser-affected zone and an alternate long- and short-dash line for the capping tube).

(a) The width of the lesion in the fat tissue.

(b) The length of the lesion in the fat tissue.

(c) The aspect ratio of the lesion in the fat tissue.

Fig. 6.

Width, length, and aspect ratio of coagulated lesion versus combination of conditions applied to forward-firing fiber and diffusing fiber in fat tissue (aspect ratio: width/length). **a:** The width of lesion in the fat tissue. **b:** The length of lesion in the fat tissue. **c:** The aspect ratio of lesion in the fat tissue.

Fig. 7.

Typical coagulation lesions of liver tissues produced with forward-firing fiber and diffusing firing fiber. **a:** Forward-firing fiber, 15 W 1 minute. **b:** Forward-firing fiber, 15 W 2 minutes. **c:** Forward-firing fiber, 20 W 1 minute. **d:** Forward-firing fiber, 20 W 2 minutes. **e:** Diffusing fiber, 15 W 1 minute. **f:** Diffusing fiber, 15 W 2 minutes. **g:** Diffusing fiber, 20 W 1 minute. **h:** Diffusing fiber, 20 W 2 minutes.

(a) The width of the lesion in the liver tissue.

(b) The length of the lesion in the liver tissue.

(c) The aspect ratio of the lesion in the liver tissue.

Fig. 8.

Width, length, and aspect ratio of the coagulated lesion versus combination of conditions applied to forward-firing fiber and diffusing fiber in liver tissue (aspect ratio: width/length).

a: The width of lesion in the liver tissue. **b:** The length of lesion in the liver tissue. **c:** The aspect ratio of lesion in the liver tissue.

Fig. 9. Typical coagulation optical image of fat tissue **(a)** and liver tissue **(b)** produced with forward firing fiber.

Fig. 10.

Image of the fat tissue ablation and temperature distribution after 8 minutes laser irradiation.

a: Optical image of laser-induced damage zone with forward firing fiber. **b:** Thermal image of laser-induced damage zone with forward firing fiber after 4 minutes. **c:** Thermal image of laser-induced damage zone with forward firing fiber after 8 minutes. **d:** Optical image of laser-induced damage zone with diffusing fiber. **e:** Thermal image of laser-induced damage zone with diffusing fiber after 4 minutes. **f:** Thermal image of laser-induced damage zone with diffusing fiber after 8 minutes.

Fig. 11.

Image of the liver tissue ablation and temperature distribution 8 minutes laser irradiation. **a:** Optical image of laser-induced damage zone with forward firing fiber. **b:** Thermal image of laser-induced damage zone with forward firing fiber after 4 minutes. **c:** Thermal image of laser-induced damage zone with forward firing fiber after 8 minutes. **d:** Optical image of laser-induced damage zone with diffusing fiber. **e:** Thermal image of laser-induced damage zone with diffusing fiber after 4 minutes. **f:** Thermal image of laser-induced damage zone with diffusing fiber after 8 minutes.

Fig. 12.

Illustration of drilling effect with forward-firing fiber in liver tissue. **a:** Laser irradiation into the tissue and the light starts to be absorbed. **b:** The temperature increases rapidly and reaches the vaporization temperature. **c:** The dehydration tissue and removal was occurred. **d–e:** The adjacent layer is exposed to the continuing laser irradiation and heated up. **f:** The heated layer is removed and the ablation front moves deeper and deeper into the tissue (drilling effect).

Fig. 13.

Illustration of the proposed mechanism by “the reservoir formed by melted lipids” with forward-firing fiber in fat tissue. **a:** The light is irradiated into fat tissue and the light starts to be absorbed. **b:** The temperature of the laser-irradiated region started to rise and reached the melting point of fat. **c:** The fat starts to melt and the small reservoir filled with melt lipid. **d–f:** The temperature of the melted lipids kept increasing beyond the melting point, the temperature of the reservoir did not reach the smoke point of fat. The oil was trap the reservoir and trapped liquid phase fat absorbs the laser light. The absorption of light by the liquid phase also leads to the thermal conduction and coagulation around the reservoir.