Minimization of thermomechanical side effects and increase of ablation efficiency in IR ablation by use of multiply Q-switched laser pulses

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ABSTRACT

Large thermal damage zones have been observed after application of free-running holmium laser pulses inside the human body as, for example, for arthroscopic surgery. The aim of our study is to reduce thermal damage by increasing the ablation efficiency, and to achieve a smooth surface of the ablated tissue. For that purpose we use a multiply Q-switched thulium laser (λ = 2.0 µm, acousto-optical QS) that emits pulse series consisting of a pre-pulse of 40 mJ energy and up to 6 ablation pulses of 100 mJ each, separated by time intervals of 60 µs. Q-switched laser pulses explosively ablate the target material. In a liquid environment, this leads to the formation of cavitation bubbles and to mechanical damage of the surrounding tissue. The pre-pulse of 40 mJ serves to minimize the cavitation effects, as it produces a small cavity that is then filled by the ablation products created by the burst of 100-mJ pulses. The pre-pulse creates, furthermore, a channel between fiber tip and target that reduces absorption losses in the liquid. Reduction of cavitation effects and channel formation are demonstrated by time-resolved photography. The use of a thulium laser instead of a holmium laser contributed to the desired reduction of thermal damage, because the penetration depth of the thulium laser light in cartilage (≈170 µm) is only half as large as with the holmium laser. The main reduction of thermal damage was, however, achieved through the use of Q-switched pulses. The short laser pulse duration of 70-150 ns created stress confinement conditions leading to a 2-3 times more efficient ablation than with free running pulses and thus to less residual heat in the tissue. The mass ablated by one burst of 6 Q-switched pulses equaled the mass ablated by a 1.5-J free-running pulse. The thermal damage zone of multiply Q-switched thulium pulses was only 1/3 as large as with free-running holmium pulses. The damage was, furthermore, less severe and the surface of the ablation craters was smoother than with free-running pulses.

Key words: Thulium laser, Q-switched pulses, multiple pulses, arthroscopy, cartilage, thermal damage, cavitation, mechanical effects, ablation efficiency

1. INTRODUCTION

Holmium laser pulses (λ = 2.1 µm) are often used for medical laser applications inside the human body, because they can be well transmitted through low-OH quartz fibers, and they are relatively well absorbed in water and biological tissues. However, thermal damage zones of up to 800 µm were observed after application of free-running holmium laser pulses for arthroscopic surgery.[1, 2] The aim of our study is to reduce thermal damage without introducing additional mechanical damage and without impairing the hemostatic action of the laser radiation. For that purpose we use Q-switched pulses instead of free-running pulses.[3] For Q-switched pulses, stress confinement conditions[4, 5] are fulfilled which lead to a more efficient ablation than with free running pulses.[6] For a given ablation depth, the residual heat deposited in the tissue is therefore smaller than with free-running pulses and, hence, also the thermal damage zone. This reduction of thermal damage is possible even though the free-running pulses already fulfill the condition for thermal confinement. A further reduction of the thermal damage is achieved by employing a thulium laser (λ = 2.0 µm) instead of a holmium laser, because the penetration depth of the thulium laser radiation (170 µm)[7] is only half as large as that of the holmium laser.

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Q-switched laser pulses lead to an explosive ablation of the target material. In a liquid environment, this gives rise to the formation of cavitation bubbles which may cause mechanical damage in the surrounding tissue.[8] To reduce the hazardous cavitation effects as much as possible, we release a pre-pulse with small energy before the ablation pulses with larger energy .[9] The pre-pulse produces a small cavitation bubble which is then filled by the ablation products of the main(=ablation) pulses. The first ablation pulse is released about 100 µs after the pre-pulse when the bubble has reached it's maximal size, and subsequent pulses follow within a sufficiently short time interval for the bubble to remain open during the whole series of pulses. When the energies of the ablation pulses are optimally chosen, the ablation products raise the pressure inside the bubble to ambient pressure, but not higher. This way, no additional cavitation effects are induced, and tissue tearing and other mechanical side effects are minimized.

The transiently empty space created by the pre-pulse is not only a prerequisite to reduce the mechanical side effects originating from the ablation pulse, but it also increases the ablation efficiency by facilitating the energy deposition in the tissue to be ablated. If the fiber tip is located at a certain distance from the tissue surface, as usually the case in clinical practice, a considerable fraction of the laser light will be absorbed in the liquid between fiber tip and application site. The channel formed by the pre-pulse bubble avoids those absorption losses.

2. METHODS

A clinical holmium laser system (Baasel Lasertech BLM 1000) was modified by insertion of an acousto-optic Q-switch into the laser resonator and use of a thulium rod as laser medium. The modified system can emit series of up to 7 Q-switched pulses during one discharge of the flash lamp pumping the thulium laser rod. The first pulse has an energy of 40 mJ at the distal fiber tip, and the energy of each following pulse is approximately 100 mJ. Subsequent pulses are separated by a time interval of 60 µs. The bursts of up to 640 mJ total energy were applied though a low-OH quartz fiber with a core diameter of 600 µm.

We used hyaline cartilage specimens from porcine knee joints obtained from a local slaughterhouse to demonstrate the tissue effects of the Q-switched pulse series in comparison to free running holmium and thulium pulses. The specimens were irradiated in saline solution under an angle of 30° between fiber and sample surface to simulate clinical conditions. The distance between fiber tip and sample before the start of the laser exposure was 500 µm, and the diameter of the irradiated spot was 800 µm. The specimens were translated by 100 µm after each laser exposure such that a cut was produced after applying a series of pulses. The repetition rate of the free-running pulses and QS-pulse series, respectively, was 1 Hz.

The dynamics of the cavitation bubbles produced at the fiber tip was investigated by flash photography with 150 ns exposure time. To determine the ablation efficiency, the profile of the ablation craters was recorded by means of optical coherence tomography (OCT). Thermo-mechanical side effects of the ablation process were assessed by light microscopic inspection of 6-8 µm thick cryo-sections through the crater after staining with Weigert's hematoxilin, light green and Safranin-O.[10]

3. RESULTS AND DISCUSSION

3.1 Bubble dynamics induced by multiply Q-switched laser pulses

Figure 1 shows that the cavitation effects can be considerably reduced by applying a pre-pulse of lower energy before the ablation pulse.[11] The volume of the bubble produced by a double pulse (40mJ pre-pulse + 100 mJ ablation pulse) is merely 1/9 of the bubble volume observed when only a single ablation pulse is applied.

The cavitation bubble dynamics during a burst consisting of a pre-pulse and 6 ablation pulses is presented in figure 2. During the whole burst duration, the bubble is considerably smaller than with a single 100-mJ pulse. The laser light reaches the tissue surface with little hindrance, since the bubble remains expanded throughout the whole burst. Some light will, however, be absorbed by the ablation products within the bubble.

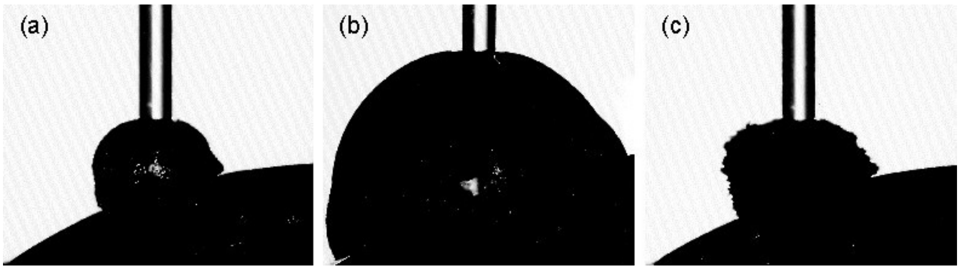


Fig. 1: Reduction of cavitation effects achieved when a pre-pulse with small energy is applied before the ablation pulse. (a) Cavitation bubble produced by a single Q-switched 40 mJ thulium laser pulse. (b) Bubble produced by a 100 mJ pulse. (c) Bubble resulting from a double pulse (pre-pulse 40 mJ + ablation pulse 100 mJ, time separation 120 µs). The ablation pulse is released, when the bubble produced by the pre-pulse is maximally expanded. Frame width 5.5 mm.

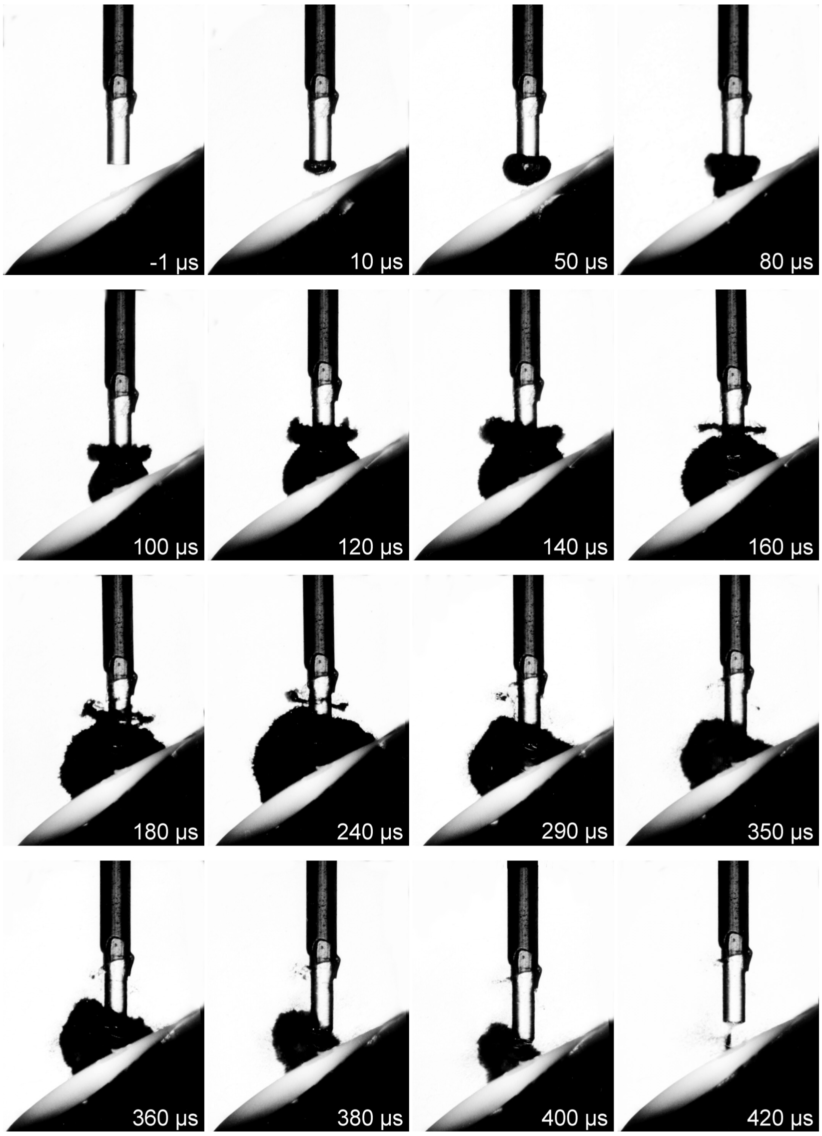


Fig. 2: Bubble dynamics during a burst consisting of a 40-mJ pre-pulse and six 100-mJ ablation pulses (time separation 60 µs, last pulse after 370 µs). The bubble forms a channel to the tissue surface throughout the whole burst duration. Frame width 5.5 mm.

3.2 Ablation efficiency

Figure 3 contains plots of the ablation efficiency vs. radiant exposure, and of the total mass ablated per burst vs. laser pulse energy. Both plots compare the results for Q-switched double pulses with those obtained with free-running thulium pulses. With Q-switched double pulses, the ablation efficiency is 2-3 times higher and the ablation threshold much lower (1/5) than with free-running pulses. The reason is that the duration of the Q-switched pulses (70-150 ns) approximately equals the time needed for a pressure pulse to cross the optical penetration depth of the laser radiation into the tissue. Under these conditions ("stress confinement"), strong thermoelastic stresses exhibiting compressive, tensile and shear components are generated[6] which locally rupture the tissue matrix. These ruptures facilitate the material ejection which is driven by the combined action of thermoelastic stresses and the explosive vaporization of the tissue water.[12] These effects lead to a reduction of the ablation threshold and to an increase of the ablation efficiency.

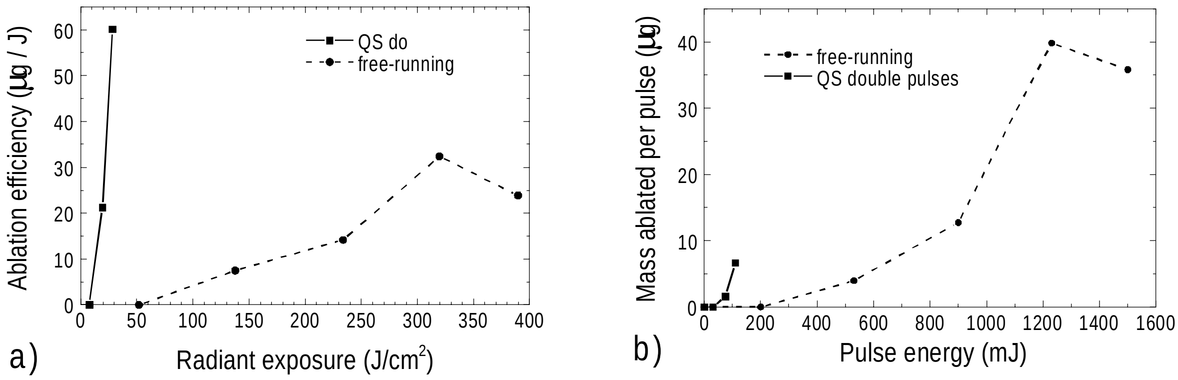


Fig. 3: Ablation efficiency (a) and ablated mass per pulse (b) for cartilage ablation in physiological saline using Q-switched thulium double pulses and free-running thulium pulses.

Even though the ablation efficiency is much higher for Q-switched double pulses than for free-running pulses, the ablated mass is larger for the latter because the available pulse energy is considerably higher (Fig. 3b). This can be changed, however, if a burst of several Q-switched ablation pulses is applied after the pre-pulse (Fig.4). With an increasing number of ablation pulses, the ablated tissue mass increases too. This increase is initially very pronounced but slows down when bursts of more than 4 pulses are used. With 4 ablation pulses (total energy with pre-pulse 440 mJ), the ablated mass is about 8 times larger than with a single free-running pulse of 530 mJ, and it reaches 86% of the amount ablated by a free-running pulse of 1.5 J. The thermal side effects of the Q-switched pulses are, at the same time, much smaller than with free-running pulses (see section 3.3, below).

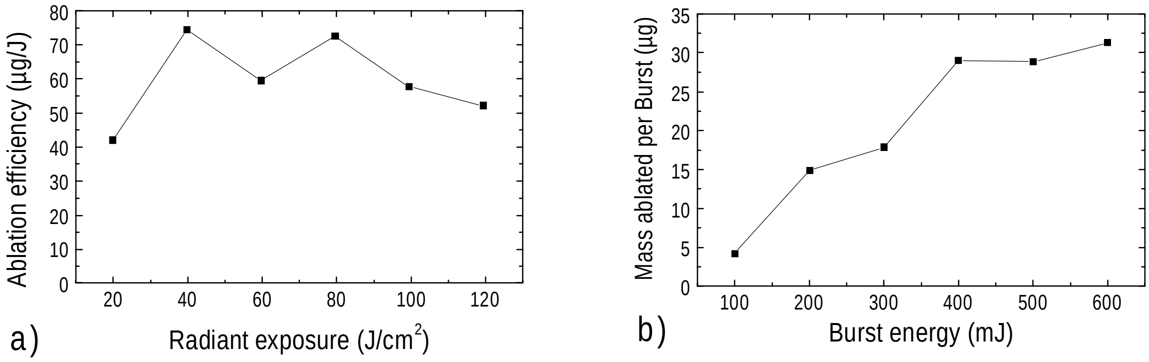
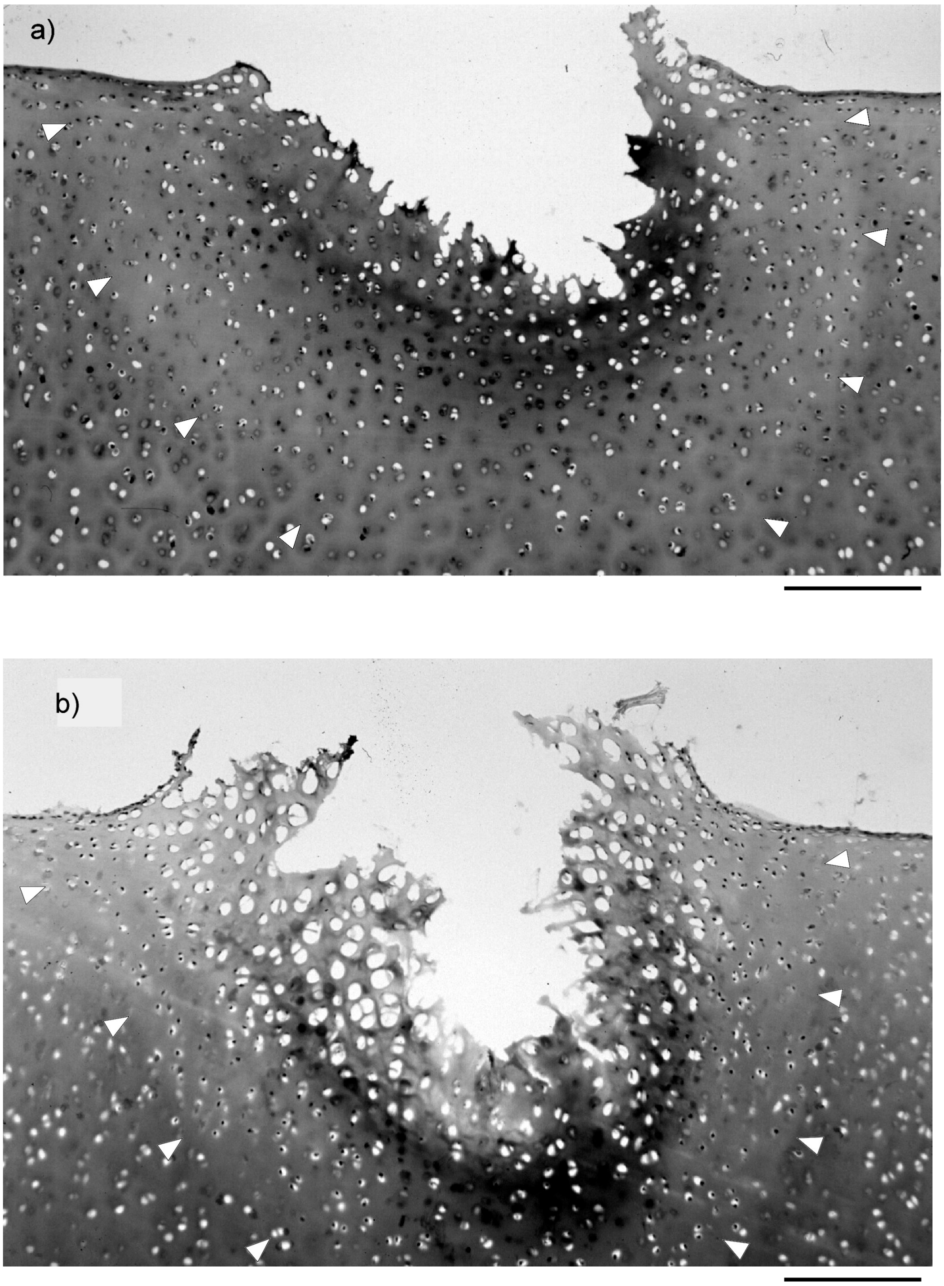


Fig. 4: Ablation efficiency (a) and ablated mass per pulse (b) for cartilage ablation in physiological saline with bursts consisting of an increasing number of Q-switched thulium pulses with individual energies of 100 mJ.

3.3 Thermomechanical side effects

The thermomechanical side effects of pulsed laser cartilage ablation can be assessed from the histologic sections presented in figure 5. They show the ablation craters produced by free-running holmium laser pulses (a), free-running thulium pulses (b), Q-switched thulium double pulses (c), and multiply Q-switched thulium pulses (d). The thermal damage zone is with free-running pulses more than two times larger (≈500 µm) than with Q-switched pulses. Moreover, the thermal damage from free-running pulses is much more severe. In the inner zone of the lesion, chondrocytes are completely absent and the connective tissue is stained more intense than healthy tissue. Such severe damage is not observed with Q-switched pulses where the complete lesion looks similar to the outer zone of the lesion from the free-running pulse. After Q-switched pulses, the cell nuclei are condensed, and the connective tissue is stained less intensely than the healthy tissue.



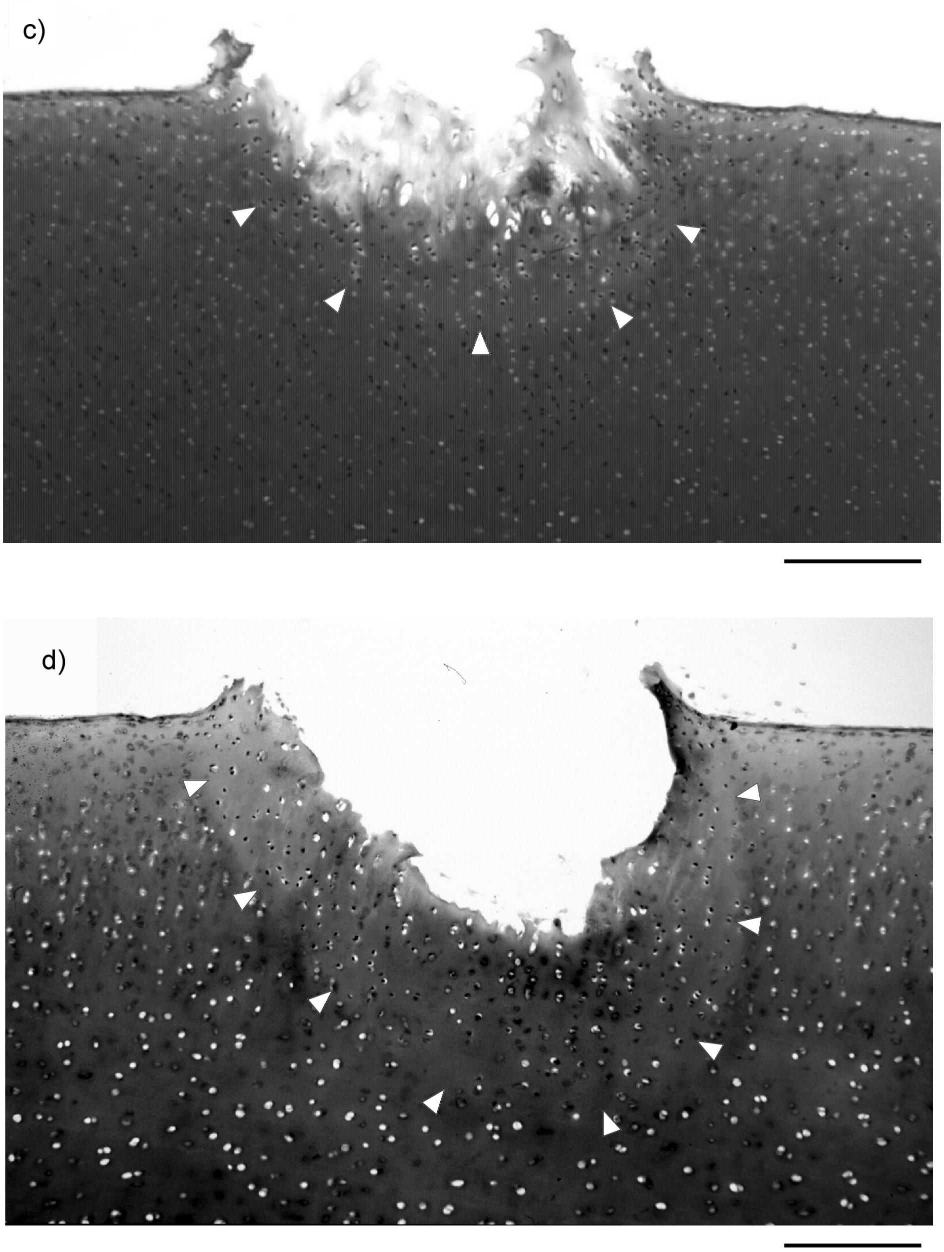


Fig. 5: Histological sections through ablation craters in cartilage produced with (a) free-running holmium laser pulses (1050 mJ), (b) free-running thulium laser pulses (1000 mJ), (c) Q-switched thulium double pulses (40 mJ + 100 mJ), and (d) Multiply Q-switched thulium-pulses (40 mJ + 3×100 mJ). The thermal damage zone (arrows) is much larger after free-running pulses, and the damage is more severe. Bursts of Q-switched pulses create smoother ablation crater walls than free-running pulses. Scale bar: 200 µm.

Remarkably, the use of free-running thulium laser pulses did not lead to a considerable reduction of thermal necrosis as compared to holmium laser pulses, in agreement with previous observations by Nishioka and Domankevich.[13] A pronounced improvement could only be achieved by applying Q-switched laser pulses instead of free-running pulses. The best results were obtained with multiply Q-switched pulses as they produce much smoother crater walls than both Q-switched double pulses and free-running pulses.

4. CONCLUSIONS

The thermal damage zone produced during in-vitro cartilage ablation in saline solution using Q-switched thulium pulses amounts to only one third of the zone of necrosis observed during ablation with free-running holmium laser pulses, The thermal damage is, moreover, less severe, and the surface of the ablation craters is smoother than with free-running pulses. The coagulative laser effect remains, nevertheless, large enough to enable a hemostatic action of the laser pulses.[14] The ablation efficiency of the Q-switched pulses is 2-3 times as high as with free-running pulses, and the mass removal with multiply Q-switched pulses is almost as high as with free-running pulses of maximum energy. Altogether, the new technique is much better suited for arthroscopic laser surgery than free-running holmium laser pulses.

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REFERENCES

1. K. B. Trauner, N. S. Nishioka, T. Flotte, and D. Patel, "Acute and chronic response of articular cartilage to holmium:YAG laser irradation," *Clin Orthopaed Rel Res* **310**, 52-57, 1995.
2. C. T. Vangsness, T. Watson, V. Saadatmanesh, and K. Moran, "Pulsed Ho:YAG laser menisectomy: effect of pulsewidth on tissue penetration rate and lateral thermal damage," *Lasers Surg Med* **16**, 61-65, 1995.
3. M. Frenz, H. Pratisto, F. Könz, E. D. Jansen, A. J. Welch, and H. P. Weber, "Comparison of the effects of absorption coefficient and pulse duration of 2.12-µm and 2.79-µm radiation on laser ablation of tissue, " *IEEE J Quant Electron* **32**, 2025-2036, 1996.
4. R. S. Dingus and R. J. Scammon, "Grüneisen-stress induced ablation of biological tissue," *Proc. SPIE* **1427**, 45-54, 1991.
5. S. L. Jacques, "Laser-tissue interactions. Photochemical, photothermal, and photomechanical," *Lasers Gen. Surg.* **72**, 531-558, 1992.
6. I. Itzkan, D. Albagli, M. L.Dark, L. T. Perelman, C. von Rosenberg, and M. Feld, "The thermoelastic basis of short pulsed laser ablation of biological tissue," *Proc. Natl. Acad. Sci. USA* **92**, 1960-1964, 1995.
7. K. P. Köstli, M. Frenz, H. P. Weber, G. Paltauf, and H. Schmidt-Kloiber, "Optoacoustic measurements of water, bone and cartilage with an infrared-OPO," *Proc. SPIE* **3601,** *"Laser-Tissue Interaction X,"* 310-318, 1999.
8. A. Vogel, E. A. Brujan, P. Schmidt, and K. Nahen, "Interaction of laser-produced cavitation bubbles with an elastic tissue model," *Proc. SPIE* **4257,** *"Laser Tissue Interaction XII,"* 167-177, 2001.
9. A. Vogel, R. Engelhardt, U. Behnle, and U. Parlitz, "Minimization of cavitation effects in pulsed laser ablation - illustrated on angioplasty," *Appl Phys B* **62**, 173-182, 1996.
10. B. E. Gerber, T. Asshauer, G. Delacretaz, T. Jansen, and T. Oberthür, "Biophysikalische Grundlagenuntersuchungen zur Wirkung der Holmium-Laserstrahlung am Knorpelgewebe und deren Konsequenzen für die klinische Applikationstechnik," *Orthopädie* **25**, 21-29, 1996 (in German).
11. A. Vogel, P. Schmidt, B. Flucke, "Minimization of thermomechanical side effects in IR ablation by use of Q-switched double pulses," *Proc. SPIE* **4257**, *"Laser Tissue Interaction XII,"* 184-191, 2001.
12. G. Paltauf and H. Schmidt-Kloiber, "Model study to investigate the contribution of spallation to pulsed laser ablation of tissue," *Lasers Surg. Med.* **16**, 277-287, 1995.
13. N.S. Nishioka and Y. Domankevich, "Comparison of tissue ablation with pulsed holmium and thulium lasers," *IEEE J. Quantum Electron.* **26**, 2271-2275, 1990.
14. H. A. Green, Y. Domankevitz, and N. S. Nishioka, "Pulsed carbon dioxide laser ablation of burned skin: in vitro and in vivo analysis," *Lasers Surg. Med*. **10**, 476-484, 1990.