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Influence of holmium:YSGG intensity on bubble formation in saline and in tissue

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ABSTRACT

Previous studies of mid-infrared ablation of tissue showed blast damage to adjacent tissue in the form of large fissures extending from the crater wall. We hypothesized that these fissures are due to the forceful expansion of a water vapour bubble within tissue. Time resolved flash photography documented an expanding vapour bubble within the tissue by the elevation of the tissue surface. The aim of this study was to determine the relation between the intensity of holmium:YSGG laser irradiation and bubble dimension in saline and in tissue. The influence of the spatial distribution of the intensity was determined by delivering 200 to 500 mJ laser pulses through a 320 μm and 600 μm diameter bare fiber, which was in light contact with porcine aorta. A holmium:YSGG laser pulse is a superposition (500 μs long) of microsecond pulses. The first part of the laser pulse contains the most intens spikes. To determine the influence of the high peak power spikes on bubble formation, the first part of a 650 mJ laser pulse was absorbed. The modified laser pulse (400 mJ) was smoother and 75 μs shorter than the original 400 mJ laser pulse.

Results: Increasing the fiber tip area by a factor of 3.5 (600 μm vs. 320 μm diameter) resulted in a decrease in the diameter of tissue elevation by only a factor of 1.25, indicating that the delivered energy determined the extent of tissue elevation. Elimination of the high peak power of the first part of the laser pulse did not decrease the dimension of the bubble in saline and of the tissue elevation. Therefore we anticipate that the extent of the blast damage in tissue cannot be reduced substantially by either reducing the fluence or by quenching high peak power spikes of the laser pulse.

2. INTRODUCTION

The development of coronary laser angioplasty has focused on the use of the XeCl excimer laser ($\lambda = 308$ nm)[1,2], because this pulsed laser was reported to be capable of precise tissue ablation with minimal adjacent tissue injury [3]. The ultraviolet light emitted by the excimer laser is strongly absorbed by protein molecules and nucleic acids (attenuation coefficient of more than 10 mm^{-1})[4], whereas mid-infrared laser light ($\lambda = 1.9$-2.1 μm) is strongly absorbed by water molecules. Hence, effective tissue ablation by pulsed mid-infrared lasers is achieved with little thermal damage to adjacent tissue [5-8]. Mid-infrared lasers are solid state lasers, which are inexpensive, reliable and easy to operate. For these reasons, they may offer an alternative to the excimer laser for coronary laser angioplasty [9,10]. Recent in vitro and in vivo studies, however, demonstrated that the ablation process with both excimer lasers[11,12] as well as with pulsed mid-infrared lasers is quite violent[13-15]. Time resolved flash photography of the ablation process documented the rapid expansion of the vapour bubble within the tissue[16] by an elevation of the tissue surface[14]. The temporal and spatial course of bubble formation in saline and of tissue elevation were

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similar. Histologic analysis of the craters after pulsed laser irradiation showed blast damage to adjacent tissue in the form of large fissures extending from the crater wall[15]. We demonstrated that these fissures are due to the forceful expansion of a water vapour bubble within the tissue[14]. Consequently, decreasing the bubble dimension will decrease the extent of the blast wave damage.

We hypothesized that the temporal and spatial distribution of the holmium:YSGG laser pulse might influence the bubble formation in saline as well as the bubble formation within the tissue. The aim of this study is to determine the relation between the intensity of the laser pulse and the bubble seize in saline and in tissue.

3. METHODS

3.1 Laser sources and delivery fibers

The experiments were performed with a mid-infrared laser (SchwartzElectroOptics, Orlando, Florida), which was supplied with a holmium:YSGG ($\lambda=2.09\ \mu m$) rod. The holmium laser pulse consisted of a 500 μs long series of microsecond spikes. The full width at half maximum was 200 μs.

During in vitro experiments, the pulse energy at the bare fiber tip (320 μm diameter) was varied from 100 to 700 mJ, resulting in fluences (energy per unit of area) at the fiber tip of 1.2 to 8.7 J/mm^2. To determine the influence of fluence on bubble formation, additional experiments were performed with a 600 μm diameter bare fiber tip. The energy was varied from 200 to 500 mJ per pulse (fluences of 0.7 to 1.8 J/mm^2).

To determine the influence of the temporal shape of the holmium:YSGG laser pulse on bubble formation, the first part of the laser pulse was absorbed as described earlier[8,17]. The holmium:YSGG laser pulse is a superposition (500 μs long) of microsecond pulses. The highest peak powers (up to 6 kW) are at the start of the laser pulse. By placing a 0.6 mm wide water filled cuvette just in front of the incoupling end of the 320 μm fiber, the first part of the laser pulse was absorbed by the liquid water. The moment that the 0.6 mm layer of water was vaporized, (at about 75 μs after the start of the laser pulse) the laser pulse was fully transmitted and coupled into the fiber. The absorbed energy (approximately 1/3 of the original pulse energy) was compensated for by increasing the voltage of the electrical power supply of the laser.

3.2 Laser-tissue and laser saline interaction

The interaction of the laser pulses with saline or tissue (porcine aorta) was investigated with time resolved flash photography as described earlier [7]. In short, at an adjustable period of time after the start of the laser pulse, a flash lamp was triggered. During the light flash (25 μs) the CCD chip of the video camera was exposed, by which fast ablation and evaporation processes were frozen at appropriate moments.

In a previous study we demonstrated that vapour bubbles are formed in saline and in tissue. The bubble formation within the tissue could be observed as a tissue surface elevation during irradiation. The rise of the intimal surface of porcine aorta was visualized by photographing the surface at a 10^o grazing angle. The bare fiber tip was positioned perpendicular to and in light contact with the target tissue, which was submerged in saline.

All data are presented as mean ± sd (n=8).

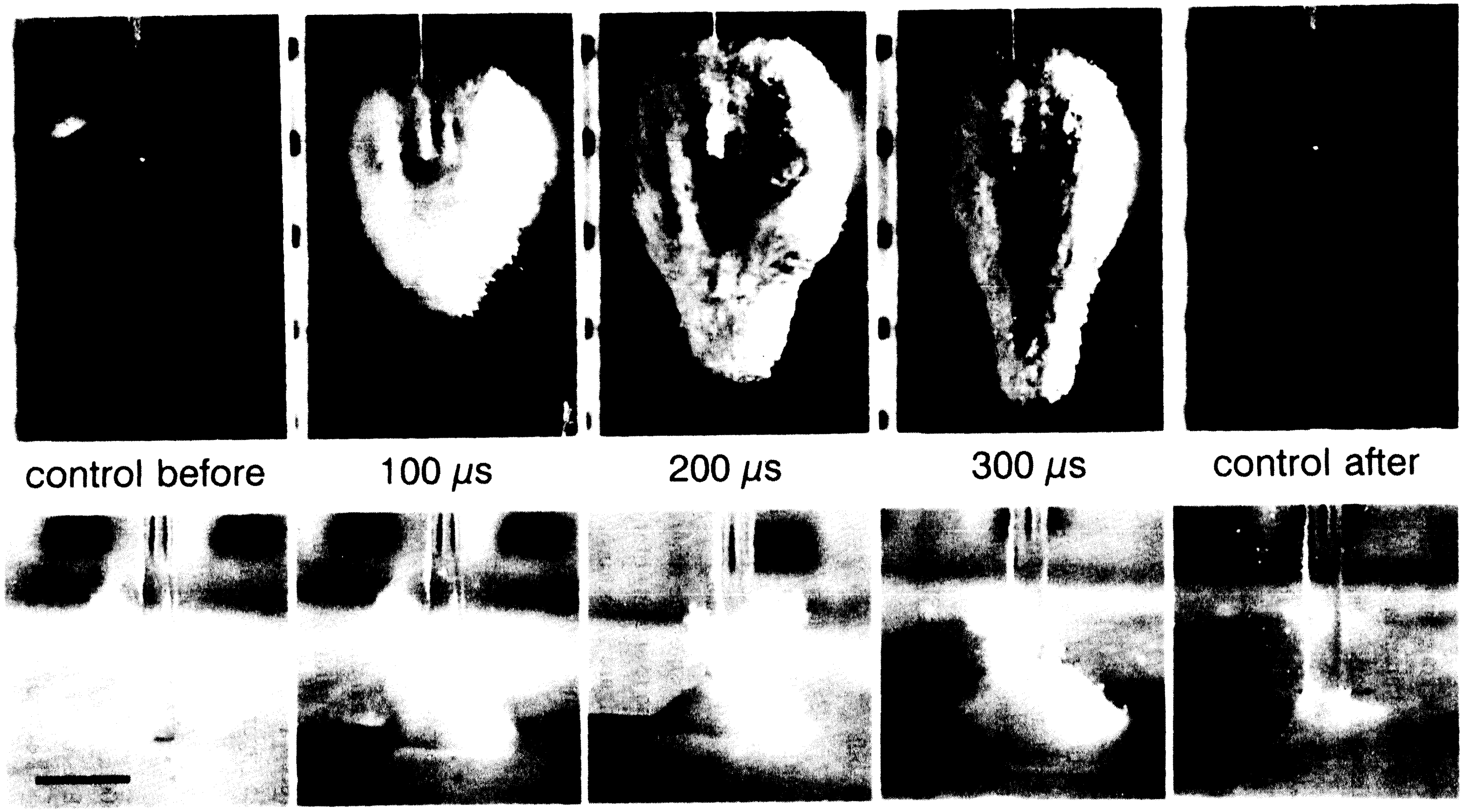

Figure 1: *Time resolved flash photography of the holmium laser-saline (top) and holmium laser-tissue (bottom) interaction before, during and after the 500 mJ holmium laser pulse. With the 320 μm diameter fiber tip submerged in saline (top), a pear-shaped water vapor bubble is formed. With the fiber tip in light contact with porcine aorta submerged in saline, a corresponding tissue elevation is observed (bottom).*

The bar represents 1 mm. (From ref. 14, with permission of the author).

3.3 Spatial distribution

The maximal diameter of the elevated tissue zone during the first, second and third laser pulse were measured as a function of the delivered energy of the holmium laser pulse (100 to 700 mJ/pulse, 1.2 to 8.7 J/mm^2) through a 320 μm diameter bare fiber. The tissue elevation diameter was compared with the diameter of the bubble diameter formed in saline.

To determine the influence of the fiber diameter on the bubble formation, the maximal diameter of the water vapour bubble formed in saline and of the tissue elevation was also measured with a 600 μm diameter fiber tip (200 to 500 mJ/pulse, 0.7 to 1.8 J/mm^2).

3.4 Temporal distribution

The influence of the temporal distribution of the laser pulse on bubble formation was determined with the 320 μm diameter fiber tip. The energy of the normal (500 μs) and the modified (425 μs) laser pulse was 400 mJ. For both laser pulses, the bubble diameter in saline and the diameter of the tissue elevation were compared.

4. RESULTS

4.1 Laser-tissue and laser saline interaction

With the bare fiber tip in contact with the intimal surface of porcine aorta, a tissue rise was observed during and after the holmium laser pulse. Figure 1 illustrates the relation, in time and in size, between tissue elevation and the expansion of the vapour bubble in saline. The maximal diameter and height of the tissue elevation was reached at approximately 300-400 μs. The collapse of the tissue, at 2-3 ms, however, was slower and later than the collapse of the vapour bubble in saline. Due to sticking of the aortic tissue to the 320 μm diameter fiber, the tissue did not return to its original position (figure 1, bottom).

The maximal diameter of the tissue elevation during the second and third laser pulse increased.

4.2 Spatial distribution

The maximal diameter of the water vapour bubble formed in saline was similar for both fiber diameters (figure 2, open circles and triangles).

During one holmium laser pulse, the maximal diameter of the elevated surface increased with the delivered energy (figure 2). Delivering 200 to 500 mJ holmium laser pulse through a 600 μm diameter fiber instead of a 320 μm diameter fiber caused a fluence decrease by a factor of 3.5. However, the maximal diameter of the elevated tissue decreased by only a factor of 1.25 (figure 2, closed triangles).

4.3 Temporal distribution

The temporal distributions of the 500 μs and 425 μs long laser pulses of 400 mJ are shown in figure 3. The diameter of the bubble in saline as well as of the tissue elevation during the first pulse was smaller for the 500 μs pulse compared to the 425 μs laser pulse (figure 2, circles and squares).

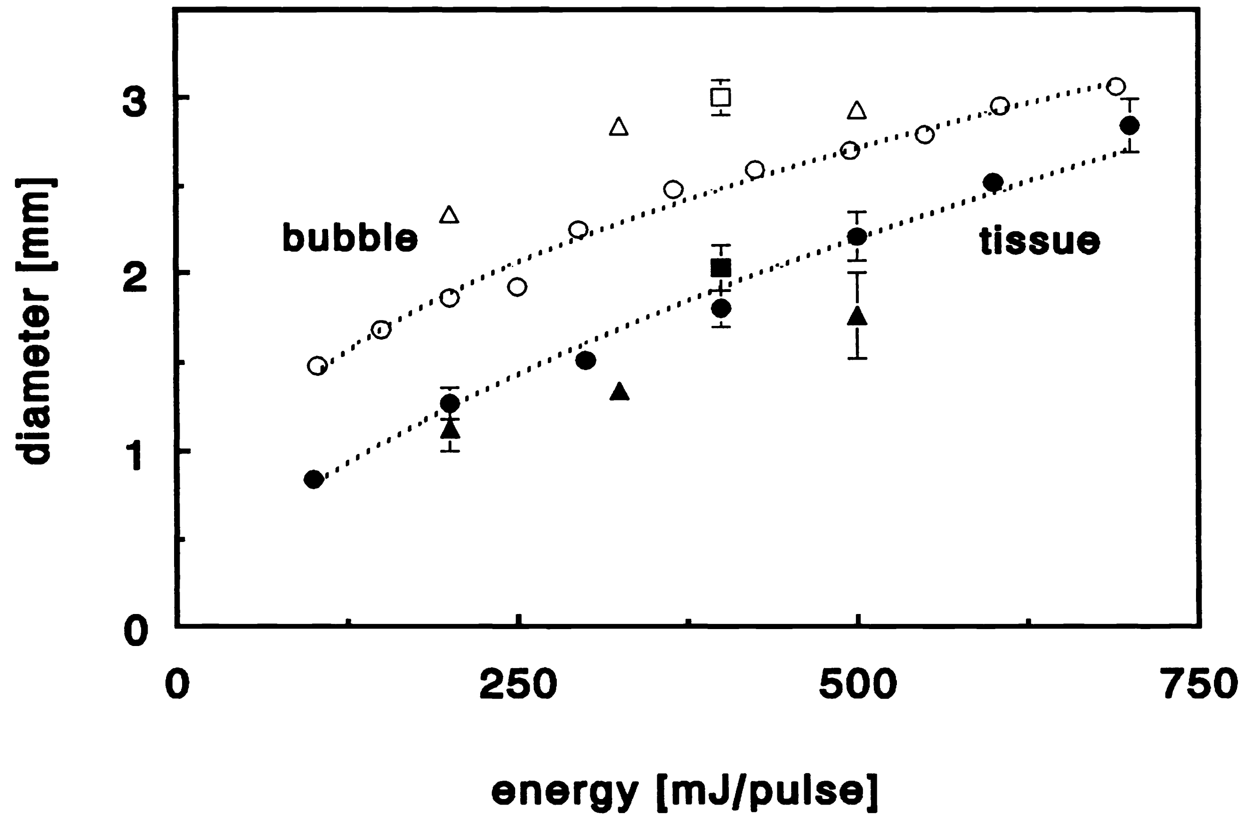

Figure 2: the diameter of the bubble in saline (open markers) and of the tissue elevation (closed markers) as a function of the delivered energy under various conditions:
circles: 320 μm diameter fiber, normal 500 μs long laser pulse;
triangles: 600 μm diameter fiber, normal 500 μs long laser pulse;
squares: 320 μm diameter fiber, modified 425 μs long laser pulse.
All data are mean ± standard deviation, n=8 per point.

5. DISCUSSION

The aim of the study was to determine the relation between the intensity of the laser pulse and the bubble formation in saline and in tissue. The principal findings of the study are:

- a decrease of the fluence by a factor 3.5 had little effect on the extent of bubble formation in saline and in tissue;
- the elimination of the high peak power spikes at the start of the laser pulse did not decrease the dimension of the bubble and of the tissue elevation.

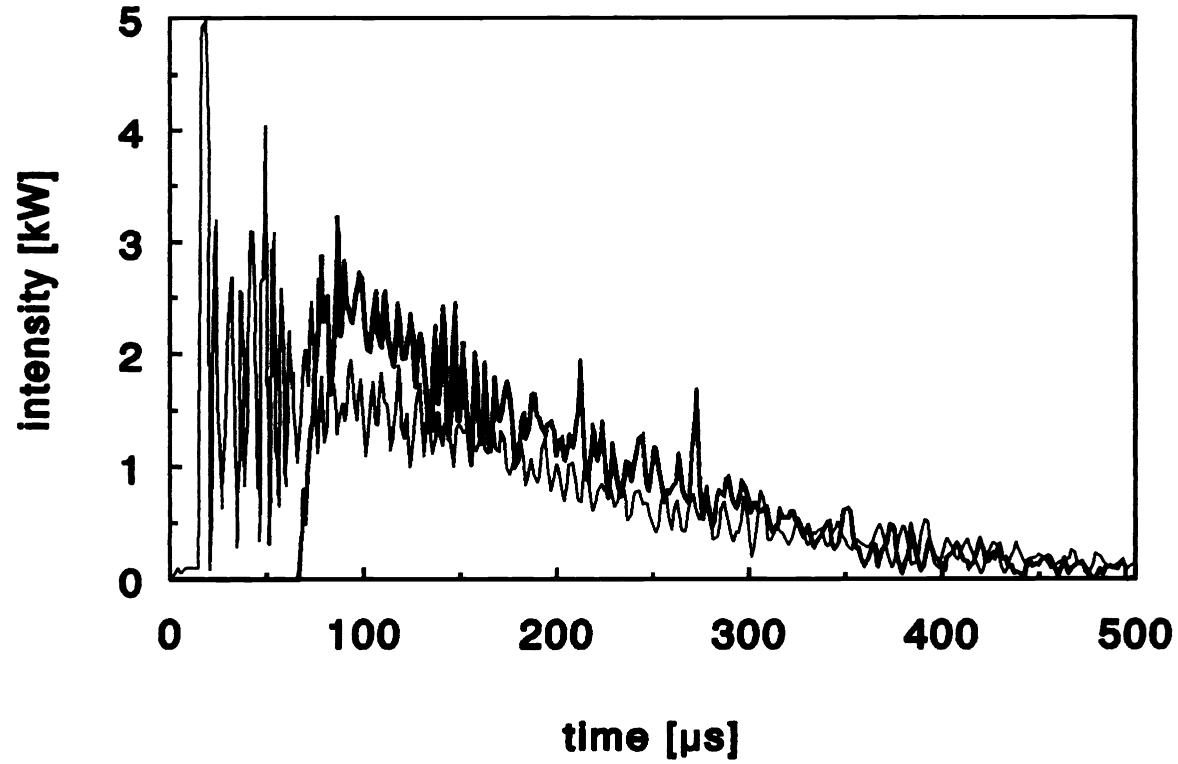

Figure 3: the temporal distribution of a 400 mJ holmium:YSGG laser pulse: thin line: a normal 500 μs laser pulse; thick line: a modified (smoothened and shortened) 425 μs long laser pulse.

Using the 320 μm diameter fiber tip resulted in high fluences (1.2 to 8.7 J/mm^2 per pulse) compared to that used in clinical mid-infrared laser angioplasty (300 to 500 mJ/pulse, 0.5 to 0.8 J/mm^2)[9]. The experiments performed with a 600 μm diameter fiber (200 to 500 mJ/pulse, 0.7 to 1.8 J/mm^2) demonstrated that changes in the fluence had relatively little effect on bubble dimensions in saline and in tissue. Thus, these results suggest that, for mid-infrared lasers, the delivered energy mostly determined the diameter of the bubble and the extent of the tissue elevation.

The similarity of the bubble formation and tissue elevation, both temporal and spatial (figure 1 and 2), indicated strongly that also within the tissue a bubble is formed[14]. The bubble expands between tissue layers, e.g. the elastic laminae of the aortic tissue, thus causing dissections. Previously, these dissections were interpreted as acoustic damage[5], due to the high peak powers of the laser pulses. Eliminating the first part of the holmium:YSGG laser pulse, which contains relatively high peak power microsecond pulses, was feasible. However, the impact of the modified laser pulse on saline and tissue was comparable to that of the original 500 μs long laser pulse. It is to be expected that the peak pressures of acoustic waves generated at the start of the laser pulse will be decreased for the modified laser pulse, because the high peak powers of the first part of the laser pulse were eliminated. However, the diameter of both the bubble in saline as well as of the tissue elevation was even slightly higher for the modified pulse. This also indicates that the tissue elevation is not due to an acoustic pressure wave. Further experiments are needed to investigate this hypothesis.

6. CONCLUSIONS

From this study we conclude that the extent of bubble formation within the tissue, which is observed as a tissue elevation, is determined by the delivered energy. We also conclude that eliminating the high peak powers of the first part of the holmium:YSGG laser pulse will not decrease the dimension of the bubble in saline and of the tissue elevation. Therefore we anticipate that the extent of the blast damage in tissue will be similar for clinically used fluences. Furthermore, we expect that the extent of the blast damage is not due to the high peak power spikes of the holmium:YSGG laser pulse.

7. ACKNOWLEDGEMENTS

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