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Tissue ablation by Holmium-YSGG laser pulses through saline and blood

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ABSTRACT

The use of 2.09 μm Ho-YSGG laser pulses for intra-vascular non-contact ablation of tissue has been investigated. Therefore the transmission and the temporal shape of the laser pulse transmitted through saline was measured. Also the interaction between the laser pulses (200 μs FWHM) and saline was studied by time resolved flash photography. Finally, porcine aorta was ablated (in vitro) through either blood or saline. The lesions and adjacent tissue were examined histologically. The penetration depth (the depth for a decrease to 1/e of the transmitted energy) of the laser pulses in saline depended on the power density (0.01 to 12.4 J/mm^2) and varied from 0.33 to 2.2 mm, respectively. The photography showed the development of a transparent water vapor cavity around the fiber tip (320 μm) during the laser pulse. The maximum dimensions of the cavity varied as function of the intensity. Within the vapor cavity the laser pulse was undisturbed. Due to this 'Moses effect in the microsecond region' porcine aorta could be ablated through up to 3 mm of saline and blood. Especially after successive laser pulses, histology showed large fissures in adjacent tissue, presumably due to the expanding vapor cavity and the layered structure of the aorta.

In conclusion, the formation of a vapor cavity during Holmium laser irradiation in physiological media enables non-contact tissue ablation and induces fissures into adjacent tissue, that may be undesirable.

2. INTRODUCTION

In laser angioplasty various wavelengths are used, ranging from the ultraviolet (eg. the excimer laser) to the infrared (eg. the Nd-YAG and Holmium laser). Due to the high absorption of Holmium laser light by tissue water, the Holmium laser may be a promising tool for ablation of tissue with little thermal damage to adjacent tissue [1,2]. The use of the Holmium laser for ablation of tissue in a non contact mode may be limited by the absorption of the laser light by blood or saline positioned between the fiber tip and the target tissue. A previous study[3], however, showed that, due to a 'Moses effect in the microsecond region', the absorption by the intermediate physiological layer was less than expected from the theoretical absorption coefficient of 3 /mm.

Another disadvantage of the Holmium laser might be the so called 'acoustic' damage induced in surrounding tissue[4]. Therefore the interaction between the Holmium laser pulses and saline was studied as function of the output energy by measuring the temporal shape of the laser pulse transmitted through physiological media and by time resolved flash photography. Finally, through either blood or saline porcine aorta was ablated in vitro.

3. MATERIALS and METHODS

3.1 Laser

A Holmium-YSGG laser (Schwartz Electro-Optics Inc., Orlando, Florida) generated 500 μs long series of microsecond pulses at a wavelength of 2.1 μm. The full width at half maximum (FWHM) of the envelope of these spikes was 200 μs. The experiments were performed at a repetition rate of 1 Hz. The laser beam was coupled into a low OH optical fiber, which had a core diameter of 320 μm. The pulse energy at the fiber tip was varied from 0.08 to 1.00 J, thus, the intensity varied from 1.0 to 12.4 J/mm^2. Pulse-to-pulse energy variation was less than 5 per cent. The laser pulse was recorded with a fast pyro-electric element incorporated in a circuit which had a rise time of 10 ns.

3.2 Laser-saline interaction

The temporal shape of the transmitted laser pulse through saline was recorded with the pyro-electric detector

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positioned beneath a glass tray which contained saline at room temperature. The fiber tip was submerged at least 30 mm in the saline. The timing of the onset of complete power transmission was measured in relation to the thickness of the saline layer between the fiber tip and the bottom of the tray (0-5 mm) for various energies (0.25 to 1.00 J/pulse). This is related to the progress of the front of the vapor cavity as a function of time. By changing the pyro-electric detector by an energy meter, it was possible to measure the transmission as a function of the thickness of the saline layer and as a function of the energy at the fiber tip. The transmission was defined as the ratio of the energy per pulse transmitted through the saline to the initial energy per pulse. The penetration depth was defined as the depth at which the transmitted energy per pulse had decreased to 1/e of the initial energy per pulse. By interpolating the transmission data, the penetration depth was determined as function of the energy at the fiber tip.

The interaction of saline and laser light at the fiber tip was investigated with time resolved flash photography as described before[3]. In short, a 25 μs flashlamp was triggered at an adjustable delay (0-1500 μs) after the start of the laser pulse. The light flash was detected by a photodiode (rise time = 1.5 μs). Simultaneously, the laser pulse was detected by the pyro-electric element. The delay time, defined as the period between the start of the laser pulse and the peak of the light flash, was measured with a dual trace storage oscilloscope. During the light flash a CCD chip of the video camera was exposed. The previous study[3] showed that during the laser pulse a pear shaped water vapor cavity was formed around the fiber tip. In the present study we measured the maximum dimension and the lifetime of this cavity as function of the energy at the fiber tip.

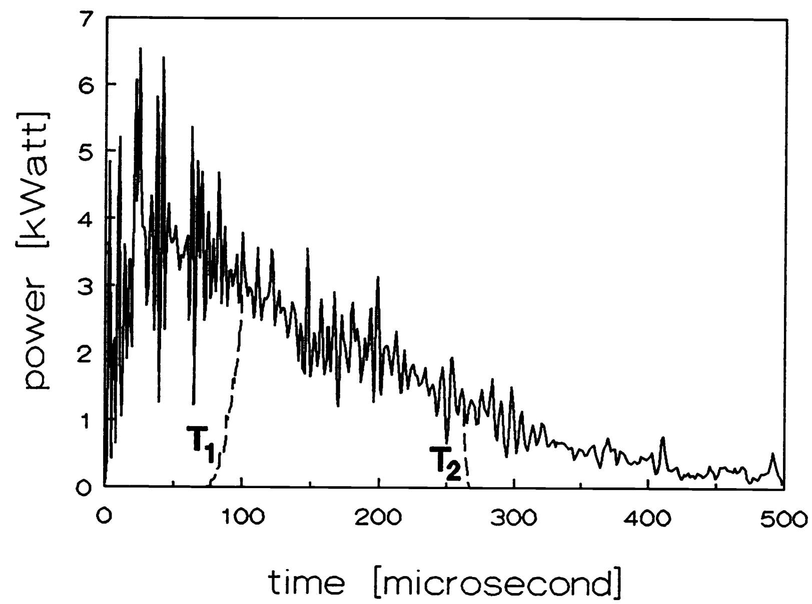

Figure 1: The temporal shape of a 1.00 J Holmium-YSGG laser pulse. The dotted line represents the estimated temporal shape of a laser pulse transmitted through 1.0 mm of saline. T_1 is the time of onset of complete power transmission through the water vapor cavity and T_2 is the timing of collapse of the vapor cavity.

3.3 In vitro non-contact tissue ablation

Within 6 hours after death, the thoracic aorta of a pig was irradiated perpendicular to the luminal surface. Thereafter the aorta was immersed in formalin 4%. After 24 hours the aortic segments were dehydrated and embedded in paraffin. Sections of 5 μm thickness were cut at intervals of 50 μm. The sections were stained with Haematoxylin and Eosin or Elastin von Gieson and analyzed quantitatively. Porcine aorta was ablated through 2 and 3 mm of saline or blood. The output energy at the fiber tip was 1.00 J per pulse. The craters and adjacent tissue were examined histologically.

4. RESULTS

The temporal shape of the Holmium:YSGG laser pulse is given in figure 1. The temporal shape of a transmitted laser pulse is part of the initial laser pulse. The relation between the thickness of the saline layer between fiber tip and bottom of the glass tray as function of the timing (T_1) of the onset of complete power transmission is given in figure 2 for various energies. The filled markers represent the measured maximum depth for complete vapor transmission. At high intensities the transmitted energy did not agree with Beer's law (figure 3). For intensities between 3.1 and 12.4 J/mm^2 per pulse, the penetration depth in saline varied from 1.3 to 2.2 mm, respectively. These are much larger than the penetration depth of 0.33 mm for intensities less than 0.01 J/mm^2 per pulse (figure 3, solid line).

Time resolved flash photography (figure 4) revealed the formation of an expanding and imploding vapor cavity during the laser pulse. The water vapor in this cavity is transparent for Holmium laser light. The expanding and imploding cavity was observed in saline at various delay times (0-1.5 ms). The maximum cavity volume was reached at 250 μs (figure 4E). The maximum depth of the cavity, eg. the maximum distance between the fiber tip and the bottom of the cavity, was reached at approximately 300 μs (figure 4F). After the implosion of the cavity at 450 μs (figure 4H) additional cavities were formed, which subsequently imploded at approximately 850 μs (figure 4J). The maximum distance between the bottom of the cavity and the fiber tip as well as the maximum horizontal radius and the maximum length of the cavity as function of the energy at the fiber tip are shown in figure 5. The lifetime of the cavity for various energies is given in figure 2 by the large symbols on the horizontal axis.

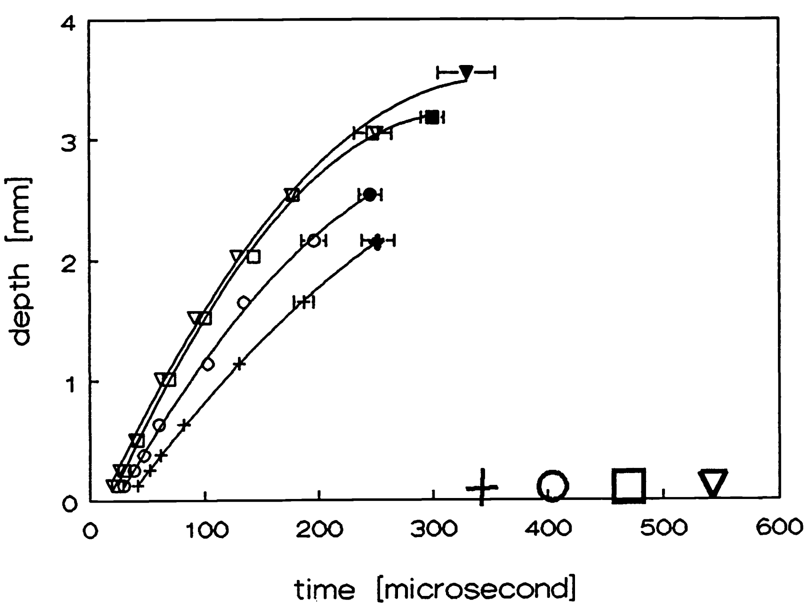

Figure 2: The front of the vapor cavity as function of the time for various energies per pulse (+, 250 mJ/pulse; o, 500 mJ/pulse; □, 750 mJ/pulse and ∇, 1000 mJ/pulse) determined from the time of onset of complete power transmission (mean ± sd, n=5) and the distance between fiber tip and the bottom of the glass tray. The filled markers represent the maximum measured depth of the front of the cavity. The large symbols on the time axis represent the lifetime of the cavity, measured by time resolved flash photography. The data are fitted with a second degree polynomial.

Tissue ablation by single Holmium laser pulse through 2 mm saline or blood was accomplished with a fiber output of 1.00 J/pulse. The diameter and the depth of the crater were approximately 0.2 to 0.3 mm. However, the damage zone after one pulse had a diameter of about 1.0 mm. After two consecutive laser pulses the depth of the crater was larger, as well as the diameter of the damage zone which consisted of fissures and irregularities in surrounding tissue. Tissue ablation through 3 mm blood was also accomplished.

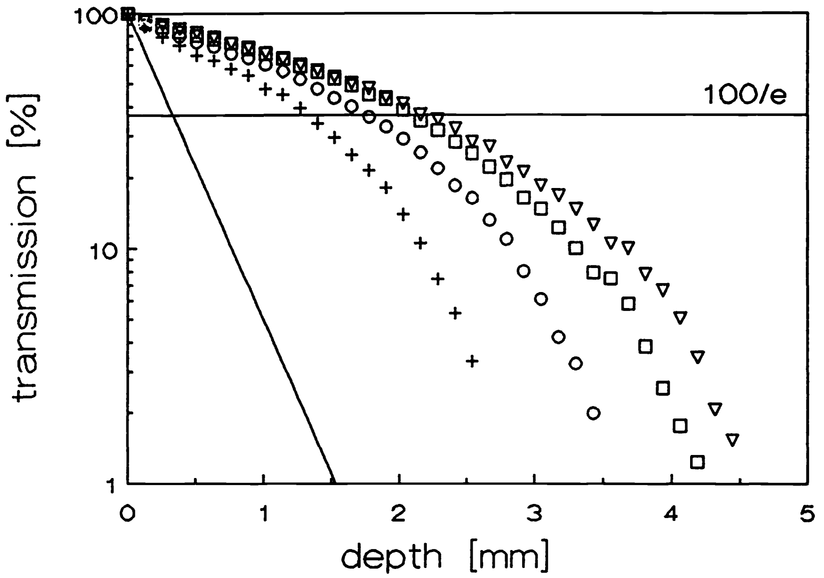

Figure 3: Transmission (in percent) of Holmium laser pulses delivered from a 320 μm fiber tip submerged in saline as function of the thickness of the saline layer between fiber tip and bottom of the glass tray (depth in mm) for various intensities. +, 250 mJ/pulse , o, 500 mJ/pulse; □, 750 mJ/pulse and ∇, 1000 mJ/pulse. The solid line represents the theoretical transmission for low intensity Holmium laser pulses.

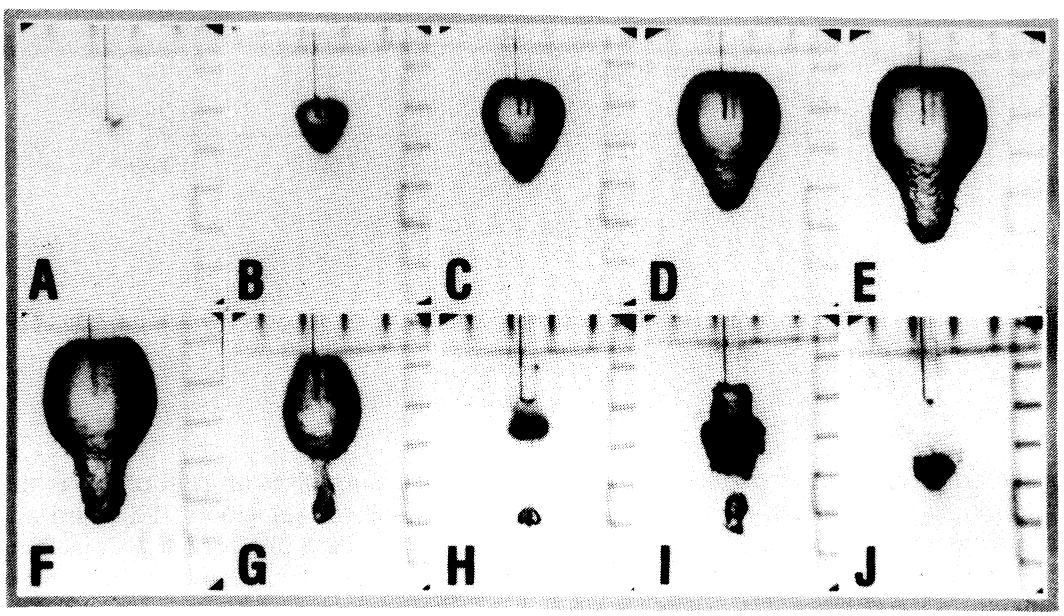

Figure 4: Vapour cavity expansion and implosion during a 0.75 J laser pulse (500 μs total pulse duration, 200 μs FWHM) delivered from a 320 μm fiber submerged in saline. Photo A was taken at 15 μs, B at 50, C at 100, D at 150, E at 250, F at 300, G at 400, H at 450, I at 600 and J at 850 μs after the start of the laser pulse. Note the millimeter scales next to the fiber tip.

5. DISCUSSION

The principal finding of this study was that the transmission of 2.1 μm laser light through saline and blood depended on the intensity of the laser pulse. Therefore the penetration depth was much larger than the expected 0.33 mm (figure 3) due to the creation around the fiber tip of a water vapor cavity which was transparent to the laser light[5].

The time resolved flash photography revealed the formation and implosion (and therefore the life time) of the water vapor cavity (figure 4). The shape and size of the cavity suggest that water is vaporized at the bottom of the cavity. The vapor condensates at the surface of the cavity. The maximum volume of the cavity does not correspond with the absorbed energy. This agrees with the postulated condensation of water vapor on the surface of the cavity. The maximum depth as function of the intensity measured by the time resolved flash photography (figure 5) corresponded reasonably with the maximum depth determined by the temporal shape of the transmitted laser pulse (the filled markers in figure 2).

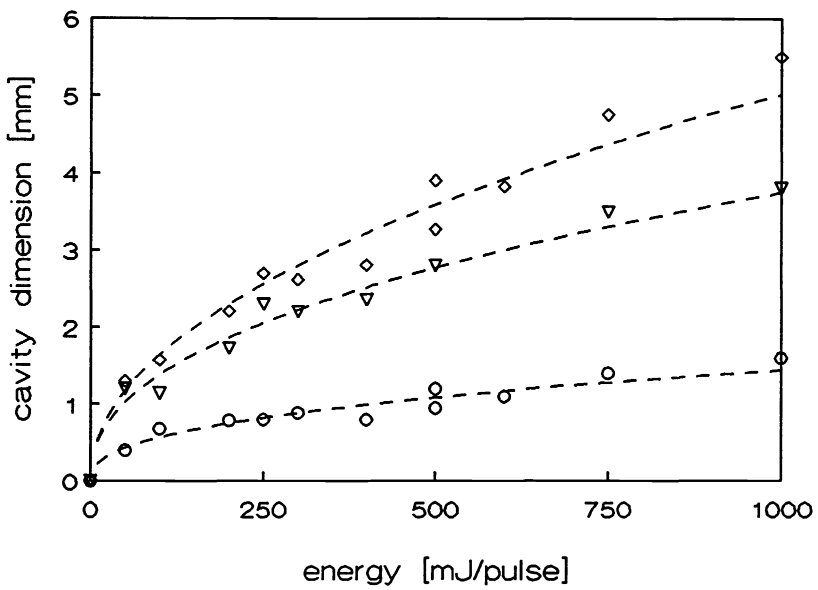

Figure 5: The maximum length (◇), depth (▽) and horizontal radius (o) of the vapor cavity as a function of the energy per pulse delivered from a 320 μm fiber tip.

For the higher energies we conclude from figure 2 that the timing of the onset of complete transmission was decreased and the maximum depth (given by the filled markers) and the velocity of the vaporization front were increased, as well as, the lifetime of the cavity, shown by time resolved flash photography,. Combining these results with the fact that water vapor is transparent for the laser light, it is not surprising that the transmission (cq. the penetration depth) is larger higher intensities (figure 3). Nevertheless, for a given energy the transmission depended on the time of the onset of complete transmission and on the time of the collapse of the cavity. The time of collapse depended on the amount of water which was vaporized and this was influenced by the distance between the fiber tip and the glass plate. So the measured transmission underestimated the real transmission. Due to the disturbance by the glass plate in the neighbourhood of the fiber tip, it was not possible to measure the lifetime of the cavity by interpreting the temporal shape of the transmitted laser pulse. Therefore the lifetime of the cavity was measured by time resolved flash photography.

The possibility of ablating tissue in a non contact mode through an opaque medium was already described by Isner et al[6]. He called it the 'Moses effect'. This 'cavitation' effect, which was also described by Sa'ar et al.[7] and Wallach-Kapon et al.[8] is based on a stacking of cavities in an air surrounding. The lifetime of these cavities was increased due to their inflation by air. If the period between two consecutive laser pulses is smaller than the lifetime of the cavity, the following laser pulse will increase the depth of the cavity. Therefore it was possible to ablate tissue through 5 mm saline or blood. In contrast to Isner's experiments[6], the fiber tip in our experiments was submerged in 30 mm saline or blood, but due to a 'Moses effect in the microsecond region', i.e. the formation of a transparent water vapor cavity during the laser pulse, it was possible to ablate porcine aorta through three millimeter of saline or blood. This finding is in agreement with the results of Aretz et al.[2] They found that it was possible to ablate through 2 mm of saline.

In conclusion, the 'Moses effect in the microsecond region' allows tissue ablation through three millimeter of saline or blood. A practical implication is that for effective tissue ablation, the fiber tip does not need to be in contact with the target tissue. A potential disadvantage of the forceful expansion of the vapor cavity are the ruptures in adjacent tissue.

6. ACKNOWLEDGMENTS

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