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Characterization of handpieces to control tissue ablation with pulsed CO_2 laser

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ABSTRACT

Focusing handpieces used for CO_2 beam delivery allow large variation of the power density in the spot depending on the distance to the tissue and hence the effect on the tissue. In contrast to the cw CO_2 laser, the pulsed CO_2 laser vaporizes tissue water instantly (:=ablation threshold), leaving a charless crater in the tissue surface. Only if the fluence is below or near threshold, the tissue effects are comparable with the cw laser.

The threshold and tissue effects were studied for focusing (f=119 mm) and collimating (∅ 3 mm) handpieces coupled to an ultrapulsed CO_2 laser. Using a special thermal imaging setup based on Schlieren techniques, the ablation threshold was determined depending on spotsize and pulse energy (1-200 mJ).

In the focus of the handpiece, the threshold was already exceeded at 1 mJ, creating holes that were larger than the theoretical expected spotsize. The ablation threshold (J/cm^2) increased for larger spotsizes. Below threshold, there is heating of the tissue resulting in coagulation. Above threshold, the exploding water vapor consumed thermal energy suppressing heating of the surrounding tissue. The gaussian shape of the collimated beam results in relatively more thermal effects. Focusing handpieces provide a wide range in power density and thus require experience from the surgeon. Collimated handpieces might be more easy to handle but offer less flexibility in tissue effect and a larger thermal zone.

1. INTRODUCTION

The CO_2 laser is being used for many years for the treatment of superficial defects e.g. on the skin. Although the laser energy is absorbed in a very thin layer in the order of 40 µm, the thermal energy will be transported to surrounding tissues depending on the fluence and the time of exposure. For the standard medical continuous wave CO_2 laser the power density reached at the tissue stays below the threshold for tissue ablation. The tissue will in sequence heat up, dehydrate, carbonize and vaporize. Using pulsed CO_2 lasers, it is possible to reach fluences above threshold for a short time. The tissue is instantly heated to 100 °C and the cell water will turn to vapor in a explosive way. In the last few years various pulsed laser systems have been introduced in the medical field which have unique characterictics. The so called super-pulsed systems produce pulses, which have a steep rise and a slower decay, with a length of 50 µs to several ms. The ultra-pulsed systems produce pulses which are block shaped in the range of 1µs to 1 ms depending on the energy. The peak power of these systems is 200-800 Watts. The laser light is applied to the tissue through an articulated arm and is then focused to the tissue by a lens. By focusing the beam, the fluence may vary enormously depending on the distance of the lens to the tissue. The fluence can be above or below threshold. Due the the gaussian character of the beam, the fluence also varies throught the spot on the tissue itself. The fluence in the center may reach above the ablation threshold while the flanks stay below. This may result in adverse thermal effects in the surrounding tissue. During clinical application the surgeon, using a handpiece or focused beam coupled into the path of view of a operating microscope, is expected to vary the distance of the handpiece to the tissue in the range of millimeters to even a few centimeters. This will result in a large variation in fluence and subsequent tissue effects. This study focuses on the effect of this variation and how critical it is as to the tissue effect. Therefore calculations and measurements were performed on the spotsizes of handpieces and a special method was used to determine the ablation threshold in the relation to spotsize and pulse energy.

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2. MATERIALS AND METHODS

2.1 The CO_2 laser and handpieces

The study was performed using an ultra-pulsed CO_2 laser system (Coherent 5000). This laser produces pulses with a peak power of 800 W with a risetime in the order of microseconds. By extending the pulse length up to a millisecond, energies of 250 mJ can be reached. The system is provided with a 119 mm focusing handpiece. Different lengths of extension tubes acting as handpiece provide preset spotsizes at the end of the handpiece. Standard handpieces are 0.2, 1.0 mm. There is also a variable handpiece in which the position of the lens to the end of the handpiece is varied resulting in a spotsizes from 0.1 to 2.5 mm. Another handpiece consists of a telescope lens system resulting in a 3 mm collimating beam.

2.2 Tissue ablation threshold

The interaction of CO_2 laser with tissue has extensively been descripted by McKenzie [1]. The ablation threshold of tissue is defined as the threshold for vaporization of water since water is the main content and absorber in tissue. For the cw laser the threshold irradiance is near 0.1 W/mm^2 . For pulsed lasers there is no need for correction for energy loss due to thermal conduction as long as the pulse is below 1 ms. The threshold fluence is near 30 mJ/mm^2 for pulsed lasers. With a absorption coefficient $\alpha = 100$ mm^{-1} , the penetration depth into tissue is 40 μm.

2.3 Gaussian beam characteristics

Using gaussian beam optics, the beam shape was calculated with the data provided by the manufacturer. The original beam was 6.5 mm diameter The theoretical shape is depicted in figure 1. In figure 2 the power density distribution through the beam is shown for various distances from the focus. The diameter of the spot is defined by the e^{-2} level relative to the maximum fluence in spot.

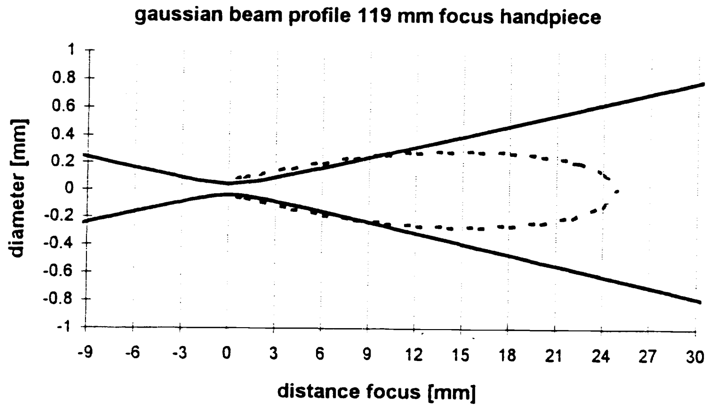


Figure 1:
Gaussian beam profile for 119 mm focus handpiece. The dotted area represents the ablating beam as explained in the text

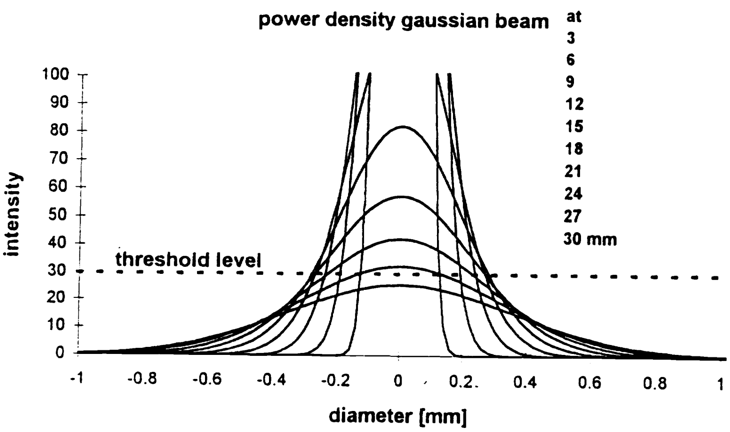
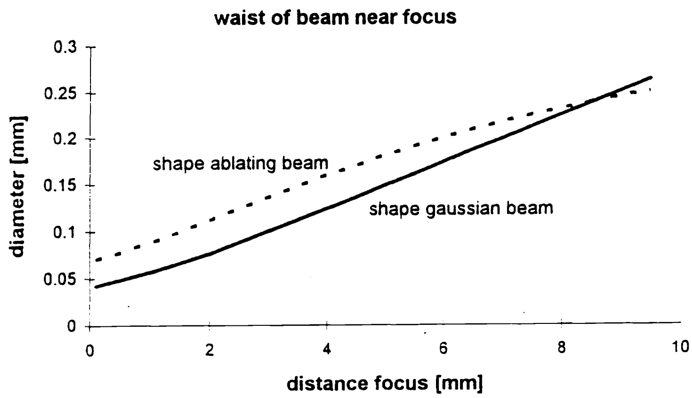


Figure 2:
Power density distribution at various levels in the beam

2.4 The 'ablating' beam

As shown in figure 2, the ablation threshold is only partly exceeded by the power density distribution through the beam. Next to the gaussian beam shape, we can define the 'ablating beam' shape which is the diameter of the beam where the power density exceeds the threshold level. In contrast to the gaussian beam shape, the shape of this beam will depend on the pulse energy. The beam profile of such an ablating beam is presented as the dotted line in figure 1 for a pulse energy of 20 mJ. In principle, the tissue that comes within the range of this area will be ablated (of course layer by layer per pulse). Looking in close-up near the waist of the beam in figure 3, it is clear that the diamter of the ablating beam is larger than the gaussian beam. This means that the theoretically defined spotsize in focus of the beam is not representative for the actual diameter of the area of ablated tissue. This area will be larger depending on the energy of the laser pulse. Already at the lowest energy level of 1 mJ, the ablating spot is larger then the 'gaussian' spot in the waist.



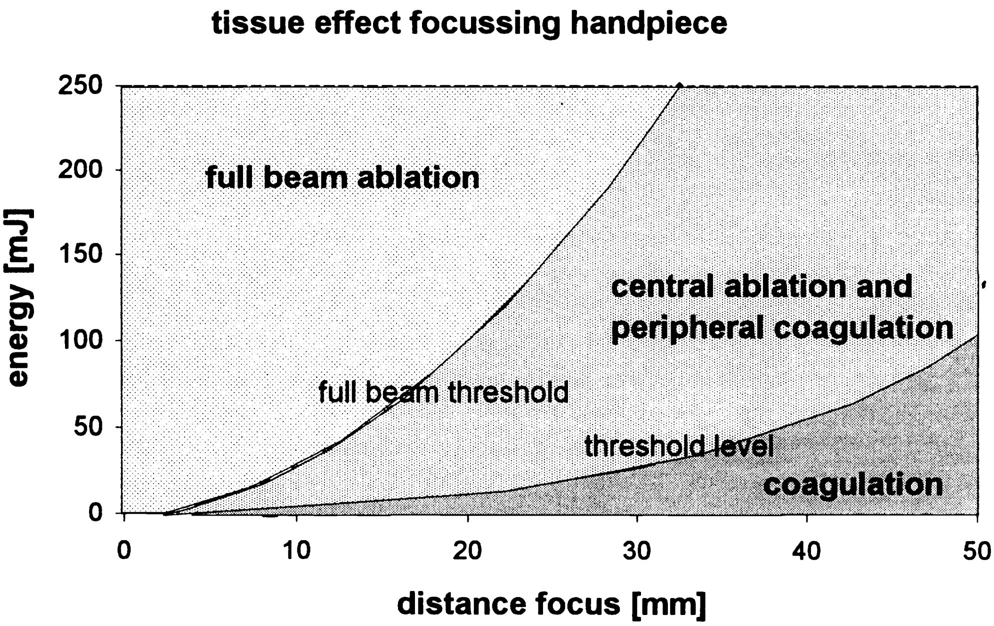
Figuur 3
Diameter of the beam near the waist with the ablating beam for a 20 mJ pulse.

At some level the 'ablating' spot and the 'gaussian' spot wil have the same diameter and, further from the focus, the 'ablating' spot will be smaller that the 'gaussian' spot. Tissue in reach of this area will partly be ablated while the flanks are just heated and coagulated. At some distance from the focus even the maximum fluence in the spot will be just below ablation threshold. This point can be detected as the starting point of ablation of tissue as will be descibed in the experiments below. Beyond this point tissue is just heated. Depending on the power applied, tissue will be dehydrated and be vaporized after all since less energy is needed to ablate dried tissue. Meanwhile, the surrounding tissue will be coagulated by conducted heat.

2.5 Predicting tissue effects

So depending on the energy of the laser pulse and the distance to the focus we can discriminate three areas: (1) the full ablating beam area, (2) the area with partial ablation and coagulation and (3) the area with only coagulation. These areas are separated by the 'full ablating beam' threshold and the ablation threshold. For each handpiece the tissue effects can be predicted by combining the focal length of a focus handpiece with the pulse energy and distance to the focus as presented in figure 4.

For a collimated handpiece the 2-D graph can be replace by an 1-D line since the diameter of the spot is comparable with one particular distance to the focus. The only variation is the pulse energy. For a collimated handpiece with a particular diameter, the energy needed to reach full beam ablation is shown in figure 5. For a 3mm handpiece 800 mJ is needed. The laser used for the experiments has a maximum pulse energy of 250 mJ so in combination with this handpiece one can always expect thermal effects around the ablating spot.



Figuur 4: Tissue effects for 119 mm focusing handpiece

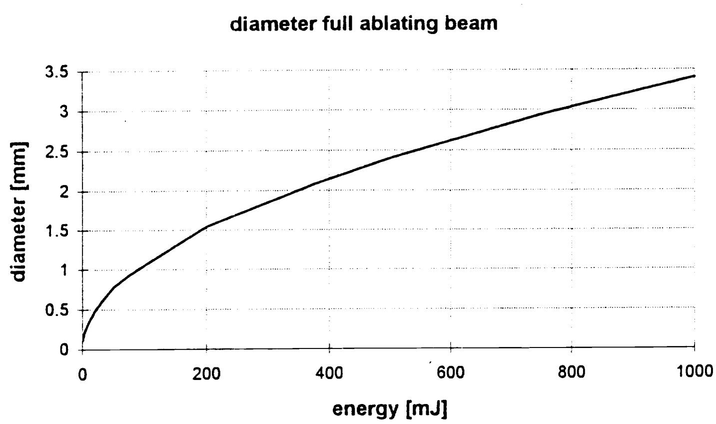


Figure 5
Energy needed to reach full ablating beam level in spot

3. MEASUREMENTS

3.1 Determination of spotsize

3.1.1 Thermal paper model

The spotsize was determined by exposing 0.3 mm thick thermal paper (used for videoprints). The paper was exposed with various energies and increasing distance between focus and paper. The ablation threshold was defined as total penetration through the paper and could be calculated from the spots.

3.2 Determination of ablation threshold

3.2.1 Thermal imaging method

The beam from the handpiece was pointed perpendicular on the surface of a water bath. The handpiece was positioned in a holder that could be translated up and down. Using a thermal imaging method based on schlieren techniques [2], it was possible to visualize the thermal energy dissipated just below the water surface. At a given pulse energy, the water was exposed with pulse trains at 3 Hz while moving the handpiece towards the water surface. For the larger distance, having the larger spotsize, color bands below the water represented thermal energy dissipated below threshold. Coming closer to the water surface, at some point the ablation threshold was reached and a thin layer of water explosively vaporized. At that moment, the colorbands disappeared due to the heavy disturbance of the water surface. The distance of the lens to the water surface at that moment showed to be reproducable when measured up to 3 times for each energy setting.

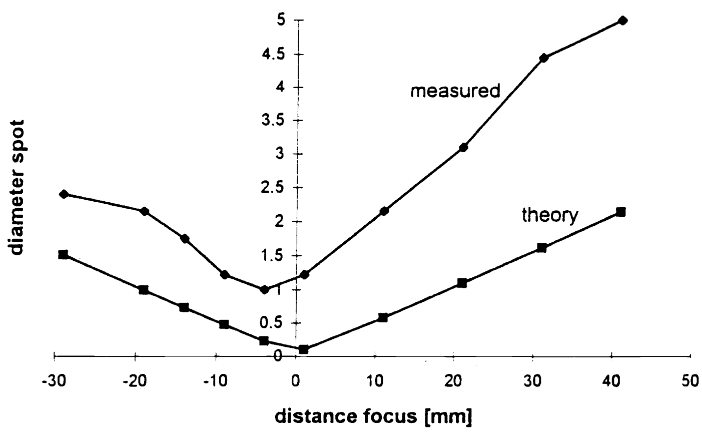
3.3 Tissue effects depending on energy and distance to focus (or spot size)

The smooth surface of porcine kidneys were irradiated with the pulsed CO_2 laser using the 119 mm handpiece and the 3 mm collimated handpiece for either equal power or equal number of pulses. In the later case, the accumulation of heat due high repetition of pulses to was prevented by waiting 1 s between each pulse. The areas of ablation and coagulation could be well distinguished.

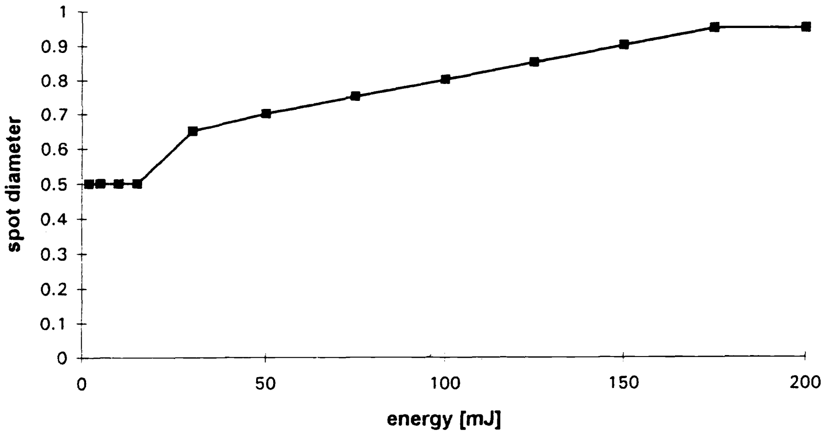
4. RESULTS

4.1 Spotsize in thermal paper

In figure 6 the measured diameter of the spot using 200 mJ pulse energy is presented in relation to the distance of the focus and in comparison with theory. The diameter of the spot in the paper is larger then theoretical spotsize in tissue. This also counts for the minimum spotsize depending on pulse energy in figure 7.



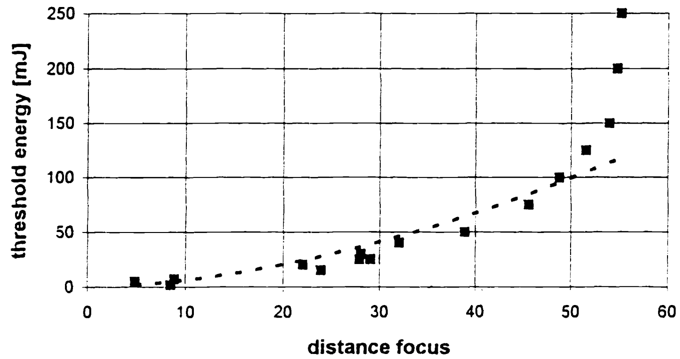
Figuur 6
Theoretical and experimental diameter of spot in thermal paper



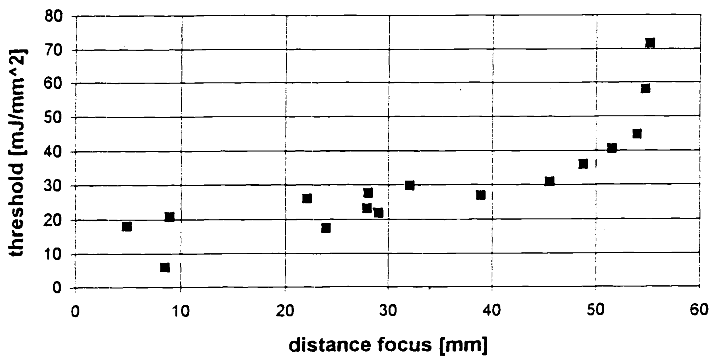
Figuur 7
Spot diameter in thermal paper near focus

4.2 Ablation threshold

The distance of the handpiece to the water surface in relation to the threshold energy is presented in figure 8 together with the theoretical curve. In combination with the theoretical spotsize, the threshold fluence can be calculated and is presented in figure 9. In threshold seems to go up for higher energies.



Figuur 8
Threshold energy in relation to distance focus, experimental data and theory (dotted line)



Figuur 9
Threshold derived from data in figure 8

4.3 Tissue effects

The effect of CO_2 irradiation on porcine kidney tissue is shown in figure 10 for a range of spotsizes (0.5, 1.5, 2.5 and 4.0) and pulse energies (10, 25, 50, 100, 150, 200 and 250 mJ) during 15 x 0.2 s exposure at 3 Hz and 5 W power.

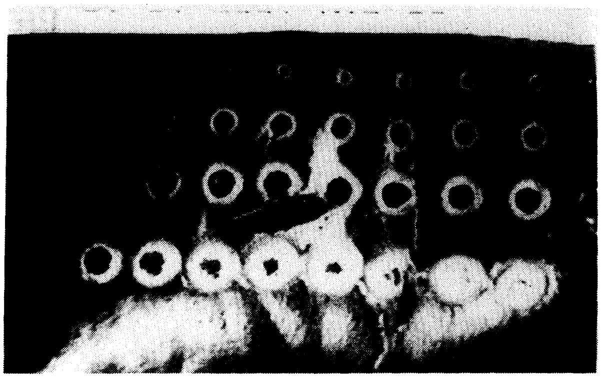


Figure 10
Tissue effects

5. DISCUSSION

5.1 Spotsize

Although it can be expected that the ablating beam causes a larger defect in tissue that the 'gaussian' spot size, the findings with the thermal paper model seem not representative for water or tissue. The threshold of the paper is propably far lower compared to water. This same effect occurs when tissue is dehydrated and starts to vaporize or burn. A better model would be a thin tissue or gel layer.

5.2 Ablation threshold

The ablation threshold derived from measurements is close to the the theoretical value of 30 mJ/mm^2. However there is some variation near the focal point. This can be attributed to the small spotsize and the low energy settings which makes it harder to determine the threshold. The rise of the threshold for larger spotsizes and pulse energies suggest that also thermal conduction can be of influence. With higher pulse energies also the pulse length increases up to 1 ms and heat conduction from the heated area is starting. Therefore more energy is needed to start ablation.

5.3 The ablating beam and tissue effects

Tissue within the range of the ablating beam will ablate by instand vaporization of water with minimal thermal damage. As stated before, below the ablation threshold, tissue will be dehydrated and if the exposure continues, it will be vaporized after all since less energy is needed to ablate dried tissue. Meanwhile the surrounding tissue will be coagulated by conducted heat. In this way the tissue effect of the pulsed laser resemble the cw CO_2 laser. Comparing the graph in figure 4 with the tissue experiments, there is a good similarity in tissue effect. This gives confidence that these graphs can be usefull to instruct surgeond how to control tissue effects using focusing handpieces.

5.4 Explosion sound

The threshold of ablation could be easily determined just by listening to the sound coming from the tissue. A very discrete snapping sound can be distinguished when the fluence in the spot is above ablation threshold. The ablation sound has a good correlation with the thermal imaging method to determine the ablation threshold. Working with two experimenters, one could tell only by the sound if ablation threshold was reached while the other experimenter used the thermal imaging. Also surgeons can train themselves in listening to the ablation sound to control tissue effects. This is especially important when working with e.g. a micromanipulator on an operating microscope where the depth of focus for viewing can be larger then the sensitive change in power density and related tissue effects. The sound can be used as an indicator when settings are going out of range.

5. CONCLUSIONS

Focusing handpieces provide a wide range in power density. Within a range of a few cm the tissue effect may vary between coagulation and a crater of 5 mm in depth.

The tissue effects can be theoretical predicted considering spotsize and pulse energy. This might help the surgeon to control CO_2 laser ablation.

Collimated handpieces might be more easy to handle but offer less flexibility in tissue effect and a larger thermal zone.

6. REFERENCES

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2. Verdaasdonk, RM, Borst C. Optical technique for color imaging of temperature gradients in physiological media: a method to study thermal effects of CW and pulsed lasers, Proc. SPIE vol. 1882, *Laser-Tissue Interaction IV*: Bellingham, 1993: 355-364