Elaboration of excimer lasers dosimetry for bone and meniscus cutting and drilling using optical fibers

Renate Jahn[1], Martin Dressel[2], Walter Neu[2], Karl-Heinz Jungbluth[1]

[1] University of Hamburg, Department of Accident Surgery, Martinistr. 52, D-2000 Hamburg 20, Germany
[2] Laser-Laboratorium Göttingen e.V., Im Hassel 21, D-3400 Göttingen, Germany

ABSTRACT

In order to optimize bone and cartilage ablation various excimer laser systems at 308 nm wavelength (pulse width 28 ns, 60 ns, 300 ns) and tapered fibers (core diameter 400 μm, 600 μm, 1000 μm) were combined.

By variing the major parameters such as fluence, pulselength, repetition rate, fiber diameter, medium, manner of application (drilling, cutting) we analysed the interaction of the excimer laser beam with different organic material (meniscus, bone tissue).

More than 300 cuts and drillings have been realized with different parameters. The ablation rate mainly depends on fluence, repetition rate and pulse duration. The achieved ablation rate was 3 μm/puls in bone. The drilling speed of the meniscus was 6 mm/s. The samples showed no carbonisation at all, when beeing cut or drilled in liquid medium. This might be a breakthrough in fiber guided excimer laser surgery.

From these and further experiments we obtain the dosimetry, which will be the basis for the elaboration of necessary operation guidelines for accident surgery.

1. INTRODUCTION

In the last years large progress has been made in cutting soft tissue with lasers. But in accident surgery many of the injured tissue used to be quite hard: bone, cartilage, etc.. Up to now the main instruments are mechanical e.g. drill, saw, knife, scissors. Their use always means a traumatic kind of tissues removal. In 30 cases of meniscectomy with mechanical instruments the knee cartilage was injured for 21 times [1]. The removal of hypertrophic callus with mechanical instruments in post fractured areas nearby nerves or vessels is often very dangerous.

The combination of an effective fiber with the high power excimer laser might be a new atraumatic tool for accident surgery using the athermical interaction of short UV-laser beam pulses with tissue (photoablation).

Hitherto the transmission of high power excimer laser pulses through optical fibers was limited by the damage threshold of conventional fused silica fibers, predominantly the damage threshold of the front or rear surface. Those fibers allow to work with a peak intensity up to 1 GW/cm2, depending on wavelength and pulse duration. Only the development of fibers with variable cross section enables to transmit more than 20 J/cm2 with easy alignment [2, 3]. At the tapered end the cross section is gradually enlarged from 3 to 9 mm within a length of less than 100 mm (Fig. 1). Thus, the entrance area is increased by about two orders of magnitude, allowing a substantial reduction of the fluence. We achieved an output energy of 250 mJ (pulse duration 28 ns) through a 1000 μm-fiber without damage of the front surface or bulk (i.e. fluence of 32 J/cm^2).

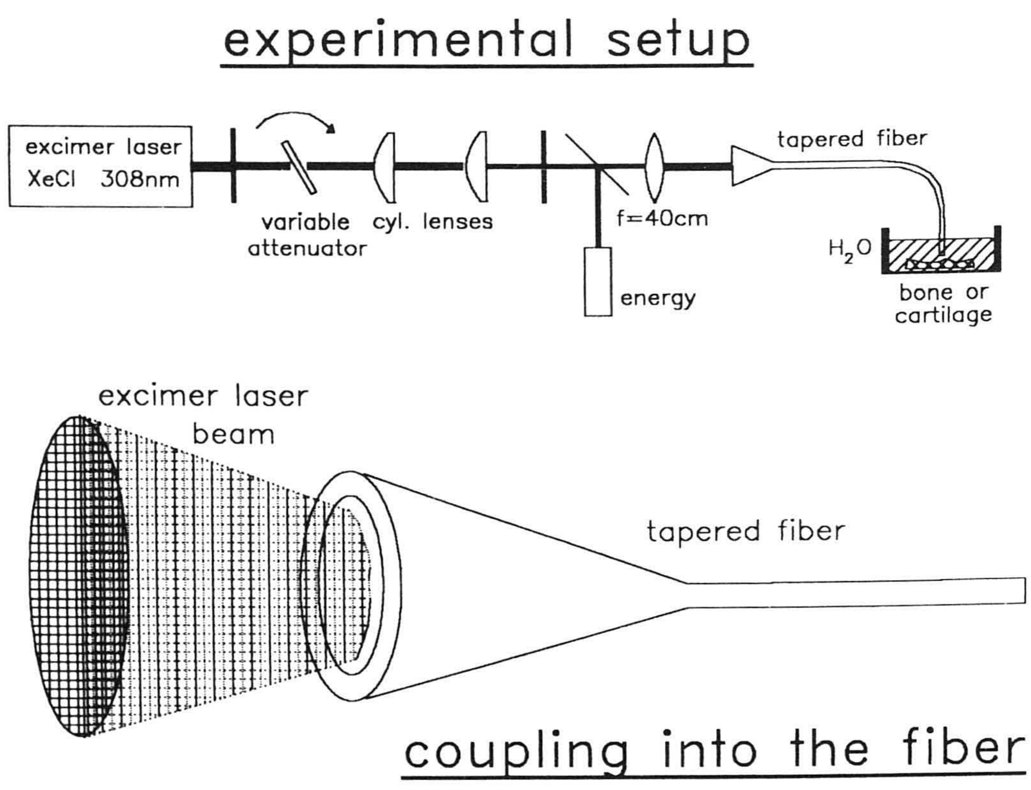

Fig. 1: Experimental setup and optical design

2. EXPERIMENT

2.1. Material and methods

Laser:

XeCl-excimer laser, wavelength 308 nm:

Lambda Physik EMG 1003i	pulse width 28 ns
Lambda Physik LPX 605iCC	pulse width 60 ns
Lambda Physik EMG 602	pulse width 250 - 300 ns

Fibers:

Tapered fibers (Heraeus Quarzglas, Hanau) made out of fused silica with fluorine-doped cladding:

core diameter:	400 μm, 600 μm, 1000 μm
diameter of the taper:	3 - 10 mm
fiber length:	200 cm

Parameter:

applied energy:	20 - 70 mJ
fluence:	3 - 18 J/cm^2
intensity:	10 - 400 MW/cm^2
repetition rate:	20 - 100 Hz

Tissues:

bone (rib)
meniscus (pig,cow)

In Figure 1 the optical setup of our experiments is shown. The energy of the excimer laser is continuously varied by a stepper motor driven attenuator and measured on-line. With a telescopical design of two cylindrical lenses the divergencies of the beam are assimilated in both directions. The excimer laser beam is focussed into the tapered part of the fiber (i.e. behind the front surface) by a spherical lens of about 400 mm focal length. The spot size of the beam inside the bulk material should be as large as the core diameter of the fiber [4].

During drilling, but not during cutting the output surface of the fiber was directly in contact with the sample, which always was immersed in water.

2.2. Results

Up to an energy of 40 mJ and for repetition rates of 30 Hz the bone ablation rates of the excimer lasers are comparable for pulse durations of 28 ns and 300 ns (Fig. 2 and Fig. 3).

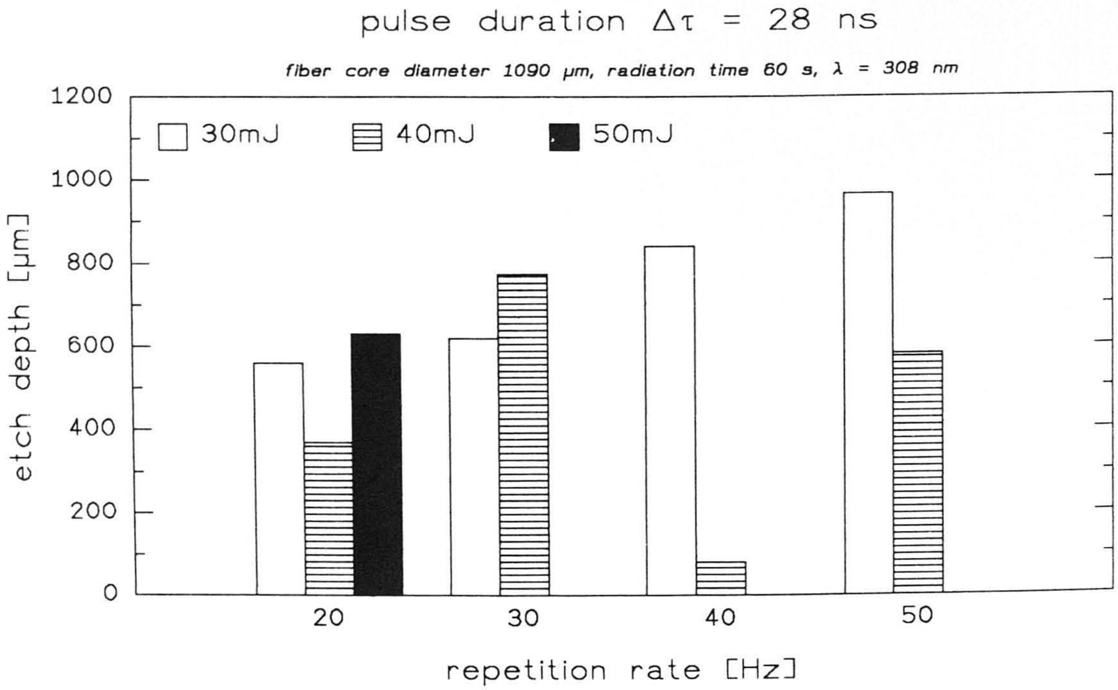

Fig. 2: Drilling holes in bone with different parameters of the XeCl-excimer laser

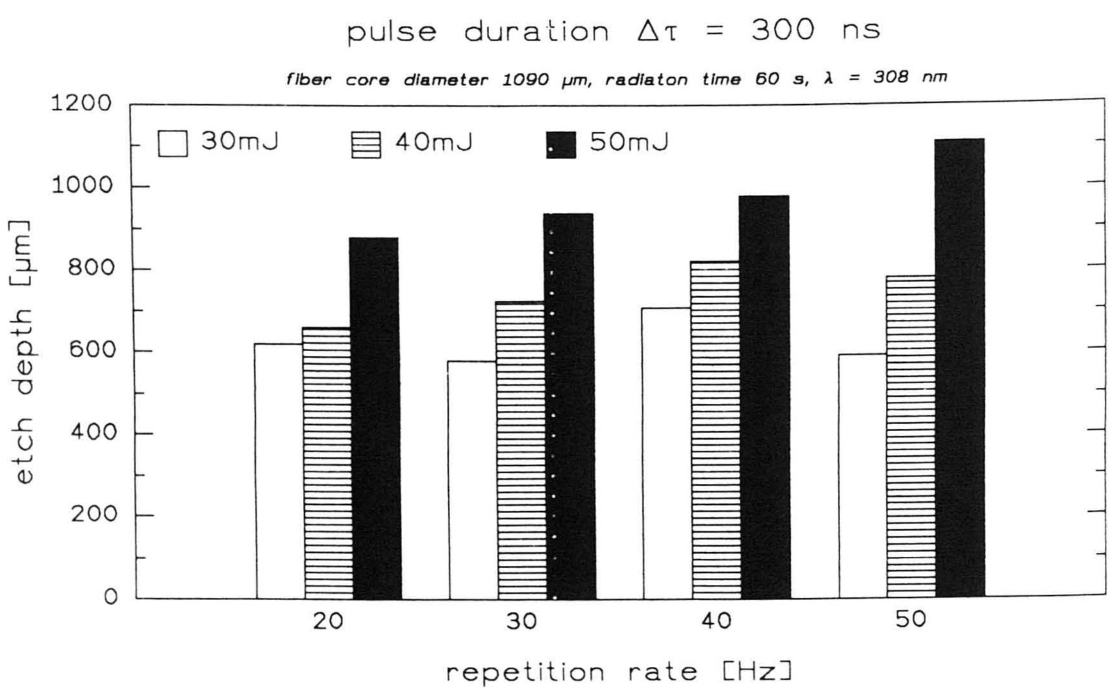

Fig. 3: Drilling holes in bone with different parameters of the XeCl-excimer laser

The output surface of the fiber was destroyed by transmitting energy of more than 40 mJ with 40 Hz repetition rate. Using lower energy (30 mJ and 20 Hz) higher ablation rates were observed for pulse duration of 300 ns. The etch depths obtained with the long pulse laser (250 ns - 300 ns) increased with energy rising up to 50 mJ and a repetition rate of 50 Hz and more (Fig. 5). 1100 μm-hole depth was achieved after 60 s exposure time (Fig. 3). On this point we reached the maximum output energy of the laser (100 mJ). At first glance, the bore depths obtained with 300 ns pulse duratation suggest an apparent superiority of the long pulse laser.

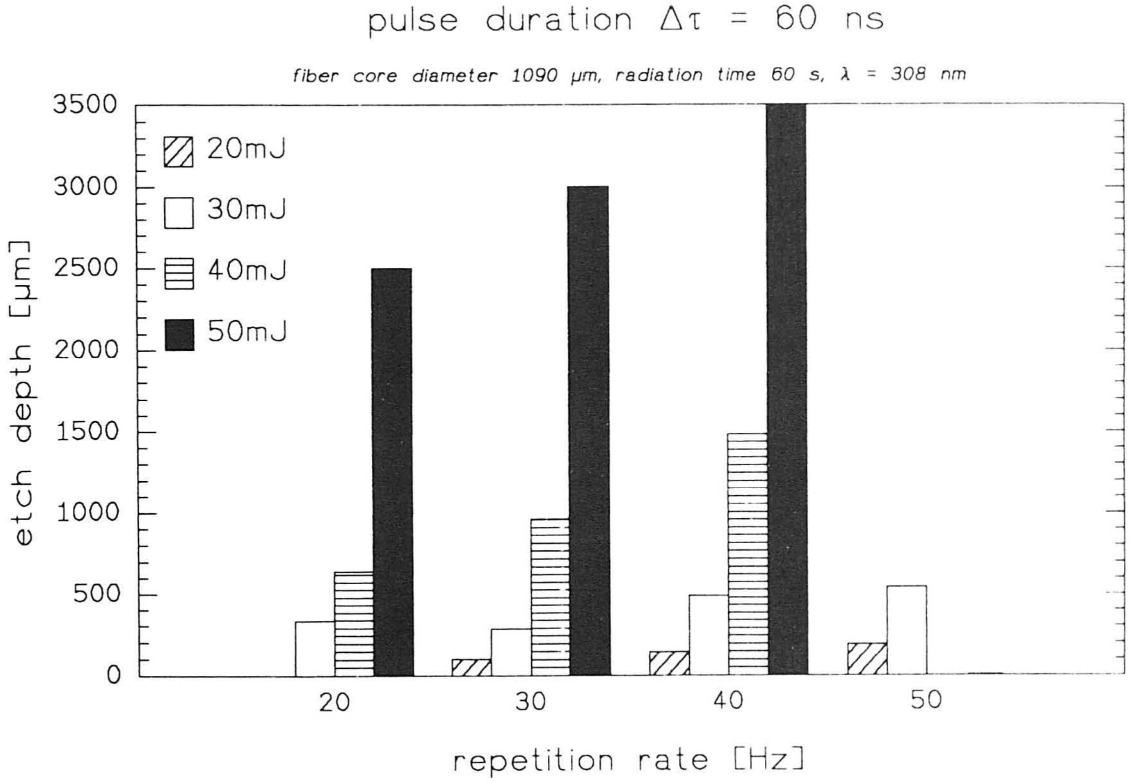

Fig. 4: Drilling holes in bone with different parameters of the XeCl-excimer laser

The excimer laser with a medium pulse duration of 60 ns allowed to transmit energies up to 70 mJ through the tapered fiber. At 60 s exposure time for example the maximum bore depth effected by 50 mJ output energy was about 3.5 mm using a repetiton rate of 40 Hz (Fig. 4). It is shown in all our experiments that the excimer laser with 60 ns pulse duration is much more effective in ablating tissue compared to 300 ns pulses, and damage of the fiber does not occur as frequently as with 28 ns pulses [5 - 7]. The ablation rate increases with rising fluence and repetition rate. For a repetition rate below 40 Hz no saturation of the ablation rate of bone was observed up to 20 J/cm^2. Higher repetition rates leed to lower ablation depth per pulse.

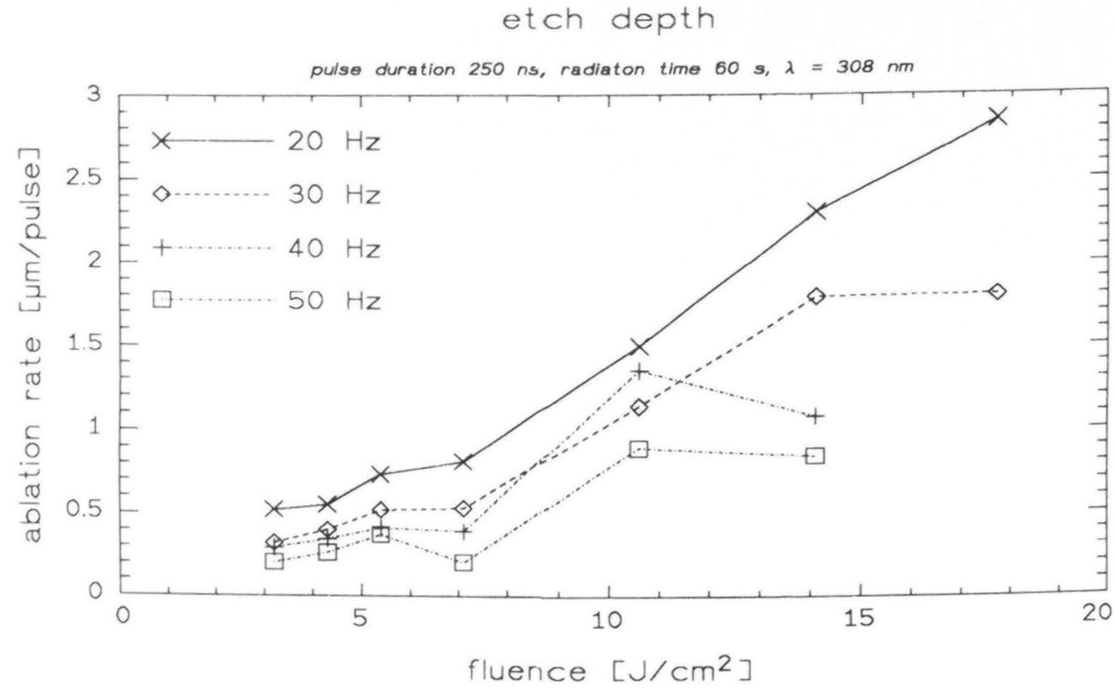

Fig. 5: The rate of bone ablation as a function of fluence for different repetiton rates of the XeCl-excimer laser

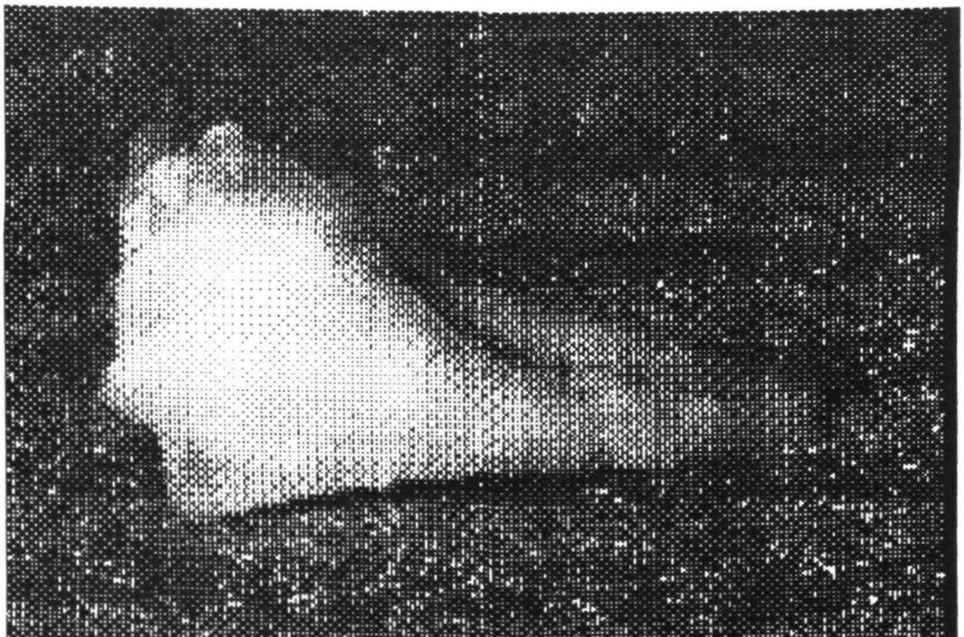

Fig.6: Cutting of meniscus. Energy 50 mJ, repetition rate 100 Hz, pulselength 300 ns, tapered fiber 600 µm core diameter, area of 4 mm x 13 mm, exposition 110 s

The drilling speed in meniscus was up to 6 mm/s. It was possible to cut a meniscus of a pig (area of 4 mm x 13 mm) during 110 s (Fig. 6).

Bone cuttings had been carried out with an ablation rate of 3 μm/pulse. Recently DINKELAKER [8] reported ablation rates for bone tissue of less than 0,86 μm/pulse using the excimer laser without any fiber coupling. Our results exceed these by a factor of four (Fig. 7).

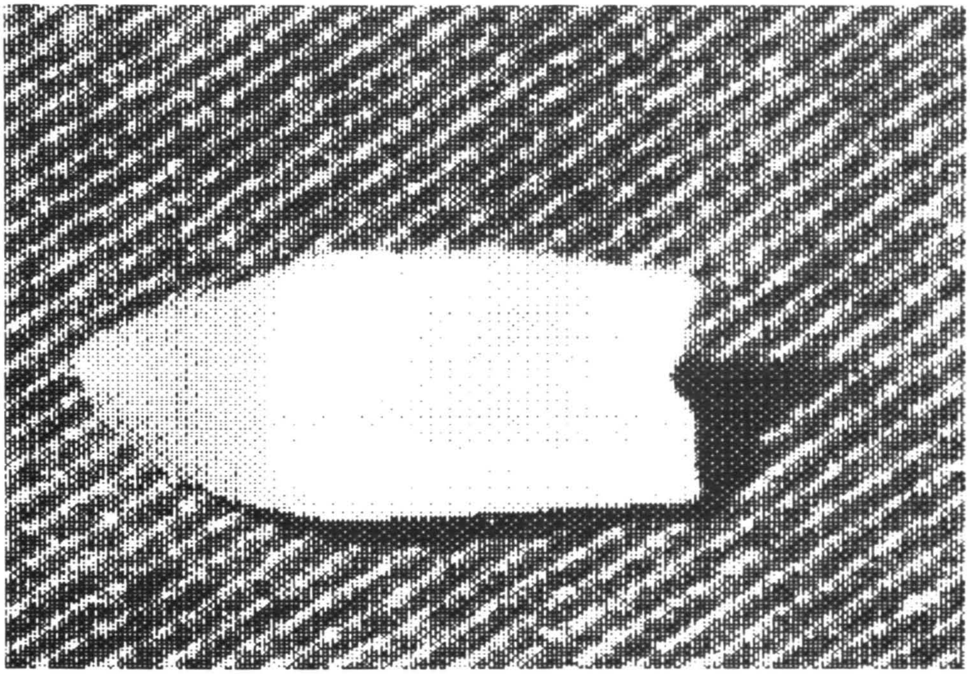

Fig. 7: Bone cut. Energy 50 mJ, repetition rate 100 Hz, pulselength 300 ns, tapered fiber 400 μm core diameter, area 4,5 mm x 7 mm, exposition 12 min

Microscopical and SEM-studies showed that the edges of bores and cuts were smooth without damage of the adjacent tissue (Fig. 8).

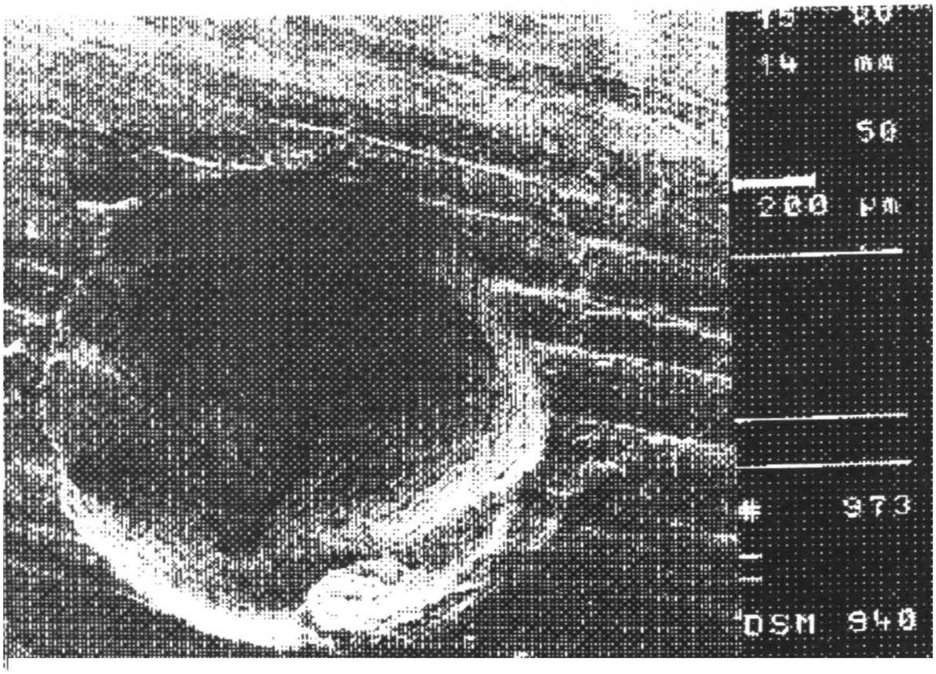

Fig. 8: Excimer laser bore in bone, SEM

Carbonisation was not observed, when the work was done under water (Fig. 9).

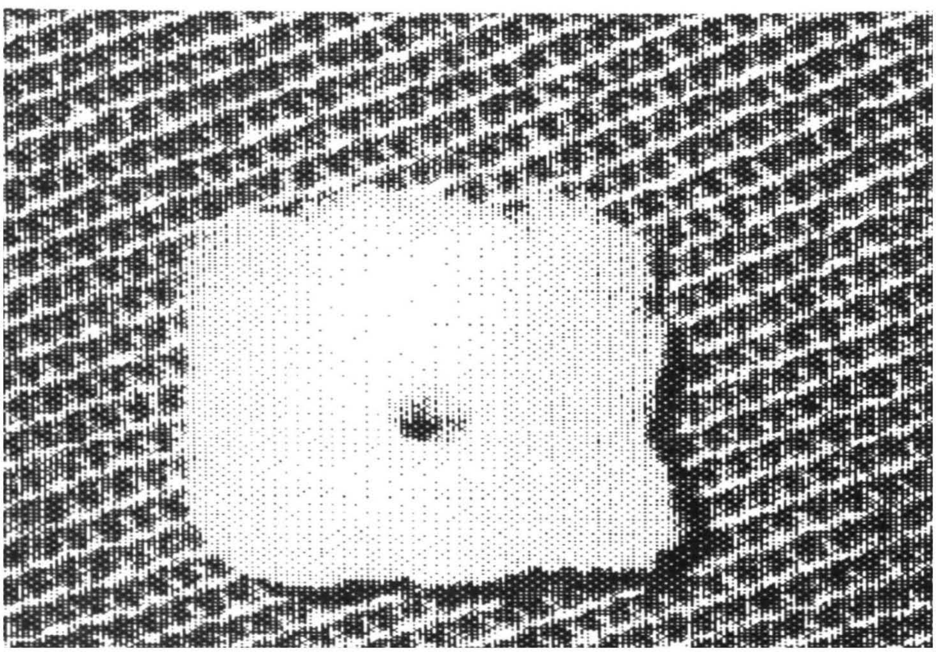

Fig. 9: Excimer laser bore in bone. 2,9 mm depth

Histological studies show a zone of only 25 - 40 μm of cells destructed by the irradiation. This may be caused by thermal effects of energy lower the ablation threshold (Fig. 10).

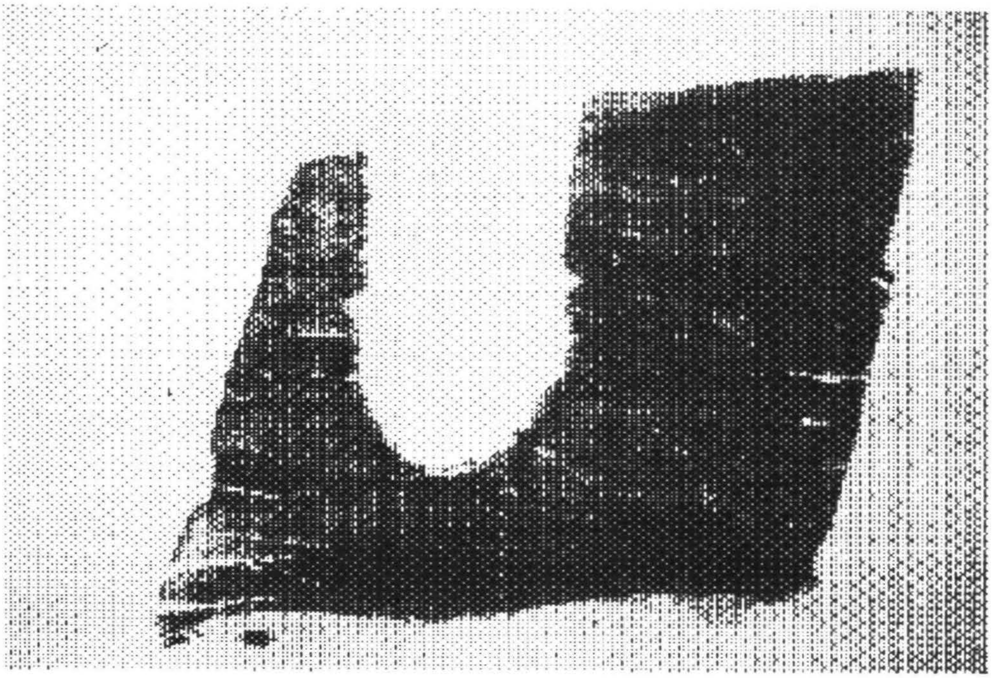

Fig. 10: Excimer laser bore in bone. 100 μm depth. This specime was embedded in metacrylat and sectioned at 8 μm. Toluidinblue 10x

One can say that the operating speeds obtained in meniscus cutting are already reasonable for surgical operations. In complicated cases, such as e.g. with knee-joint injuries of the rear meniscus, the operation can be performed using fiber guided laser technology, which is much less traumatic than the conventionally used mechanical cutting techniques.

3. ACKNOWLEDGMENTS

The authors wish to thank Dr. U. Grzesik, Dr. H.F. Klein, H. Fabian and Dr. J. Kesper; this work was generously supported by Heraeus Quarzglas, Hanau and Lambda Physik, Göttingen. We thank Prof. Dr. Liehrse from the University of Hamburg, Institute of Neuroanatomy for the preparation of the SEM specimes.

4. REFERENCES

1. W. Siebert, "Der Laser in der arthroskopischen Chirurgie", 6th Annual General Meeting of the German Laser Association, 19.-21.Sep. 1990, Berlin.

2. K.O. Greulich, H. Hitzler, N. Leclerc, J. Wolfrum, "Transport of High-Power UV-Laser Pulses through Fibers with Variable Cross-Section (Taper)", Laser und Optoelektronik 20 (4) pp.58-61, 1988 (in German).

3. M. Dressel, W. Neu, H. Gerhardt, "Fused Silica Fibers for Transmitting High Power Excimer Laser Pulses", Laser und Optoelektronik 22 (5) p.76, 1990 (in German).

4. "Tapered Fluosil Fibers to transmit UV Laser Radiation", Lambda Highlights No. 25, October 1990

5. R. Jahn, M. Dressel, H. Fabian, H. Gerhardt, J. Kesper, K. F. Klein, H. U. Langendorff, W. Neu, U. Sowada, K. H. Jungbluth, "Excimer Laser and Tapered Fibers - A Breakthrough in Fiber Assisted Cartilage and Bone Ablation. Short Note." Laser Med Surg 6 (2) pp.77-80, 1990 (in German).

6. R. Jahn, M. Dressel, H. Fabian, K. F. Klein, H. U. Langendorff, W. Neu, K. H. Jungbluth, "Bone Drilling with Fiber Guided Excimer Laser Beam" Laser Med Surg 6 (4) 1990 (in German). in press

7. "Ablation of Bone and Cartilage with 308 nm Radiation guided by a new Type of Fiber Optics", Lambda Highlights No. 25, October 1990

8. F. Dinkelaker, "Die Co_2-Laser-Osteotomie", Habilitation Surgery Clinic FU Berlin, Department of Accident Surgery 1989