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Initial clinical experience with the picosecond Nd:YLF laser for intraocular therapeutic applications

Gerd Geerling, Johann Roider, Ursula Schmidt-Erfurt, Kester Nahen, El-Sayed El-Hifnawi, Horst Laqua, Alfred Vogel

Abstract

***Aims/background*—Compared with nanosecond (ns) pulses of conventional Nd-YAG lasers, picosecond (ps) laser pulses allow intraocular surgery at considerably lower pulse energy. The authors report initial clinical experiences using a Nd:YLF ps laser for the treatment of various indications for photodisruption.**

***Methods*—A Nd:YLF laser system (ISL 2001, wavelength 1053 nm) was used to apply pulse series of 100–400 µJ single pulse energy at a repetition rate of 0.12–1.0 kHz. Computer controlled patterns were used to perform iridectomies (n=53), capsulotomies (n=9), synechiolysis (n=3), and pupilloplasties (n=2). Other procedures were vitreoretinal strand incision (n=2) and peripheral retinotomy (n=1). For comparison, 10 capsulotomies and 20 iridotomies were performed with a Nd:YAG ns laser. The ps laser cut of an anterior capsule was assessed by scanning electron microscopy (SEM).**

***Results*—Open, well defined iridectomies (mean total energy 4028 mJ, mean diameter 724 µm) were achieved at first attempt in 92% of the cases. In 64% an iris bleeding and in 21% an IOP increase of >10 mm Hg occurred. All capsulotomies were performed successfully (mean energy 690 mJ/mm cutting length) but with a high incidence of intraocular lens damage. The attempted vitreoretinal applications remained unsuccessful as a result of optical aberrations of the eye and contact lens. Although ps laser capsulotomies and iridectomies required much higher total energy than ns procedures, the resulting tissue effects of the ps pulses were more clearly defined. SEM examination of a ps incision of the anterior lens capsule demonstrated, nevertheless, that the cut was more irregular than the edge of a continuous curvilinear capsulorhexis.**

***Conclusion*—Series of ps pulses applied in computer controlled patterns can be used effectively for laser surgery in the anterior segment and are considerably less disruptive than ns pulses. The ps laser is well suited for laser iridectomies while the ns laser is preferable for posterior capsulotomies. As vitreoretinal applications remained unsuccessful, the range of indications for intraocular photodisruption could not be extended by the ps laser.**
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Department of Ophthalmology, Medical University of Lübeck, Lübeck, Germany
G Geerling
J Roider
U Schmidt-Erfurt
El-S El-Hifnawi
H Laqua

Medical Laser Centre Lübeck, Lübeck, Germany
K Nahen
A Vogel

Correspondence to:
Dr G Geerling, Moorfields Eye Hospital, City Road, London EC1V 2PD.

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Since the introduction of intraocular photodisruption by Krasnov,[1 2] Aron-Rosa *et al*,[3] and Fankhauser *et al*,[4] capsulotomies and iridectomies have become standard indications for a Nd:YAG laser treatment.[5] In clinical practice, pulse duration of 3–10 nanoseconds (ns), at energies of 0.5–10 mJ are used to create a plasma resulting in tissue evaporation at the application site. The expansion of the laser plasma causes shock wave emission and cavitation bubble formation. At a pulse energy of 5 mJ, the shock wave pressure can reach over 20 kbar, and the cavitation bubble can grow to a size of about 2 mm.[6 7] The plasma associated tissue evaporation contributes to the desired effect whereas shock wave and cavitation generate disruptive effects and can cause unwanted collateral damage.[8 9] In the vicinity of sensitive structures such as the retina, it is more desirable to achieve laser effects of a more incisive nature with as few disruptive effects as possible. When the laser pulse duration is reduced from the nanosecond to the picosecond (ps) range (30–40 ps), the threshold for optical breakdown drops to approximately 20 µJ—that is, to about 7% of the energy needed with the ns laser.[9] Therefore, the disruptive effects of the individual laser pulse can be drastically reduced with ps pulses,[6 7 10] so that considerably finer tissue effects can be achieved. It should be emphasised that this reduction of disruptive effects is only possible with single ps pulses, but not with the mode locked laser systems used in the early days of photodisruption.[3] These earlier systems emitted trains of 7–12 ps pulses in very rapid succession (approximately 7 ns time difference) which produce cumulative mechanical effects similar to those generated by single ns pulses.[11] The pulse repetition rate in the present ps laser systems is, in contrast, so slow (≤1000 Hz) that the mechanical action of subsequent pulses does not add up to form cumulative effects. In this study, we report on our initial clinical experiences with a Nd:YLF ps laser for various clinical indications and compare it with the performance of the Nd:YAG ns laser.

Material and methods

We used a Nd:YLF laser (Intelligent Surgical Laser, model 2001) emitting single pulses of 40 ps at a wavelength of 1053 nm and an energy of 20–400 µJ. The focusing angle is 20° and the spot diameter 15 µm. To make clinical use of the microeffects resulting from low energy ps pulses, series of pulses must be applied. The repetition rate can be varied between 10 and 1000 Hz. The pulses can be applied by manual aiming or in various computer controlled application patterns (line, curve, circle, spiral, rectangle). The maximum size of each pattern is 2 mm.

We performed 53 iridectomies, two pupilloplasties, five anterior and four posterior capsulotomies, and three synechiolysis and attempted to dissect peripheral vitreoretinal strands or retinal tissue in three cases. For iridectomies we selected a spiral pattern, whereas a line pattern was used for capsulotomies, synechiolysis, and vitreoretinal applications. Depending on the indication, the Nd:YLF laser focus was set 50 µm posterior or anterior to the target laser focus to avoid damage to adjacent structure. For comparison, 10 posterior capsulotomies and 20 iridotomies were performed with a conventional ns laser (Zeiss Visulas YAG). For each treatment a specific contact lens (Ocular Instruments OAIY Abraham lens for iridectomies, Meridian CGP for capsulotomies, Goldmann three mirror lens for applications in the fundus periphery) was used. The intraocular pressure was measured before surgery and 1 and 4 hours after each operation using a Goldmann applanation tonometer. The therapeutic effect of every iridectomy was tested postoperatively in a provocation test with a topical mydriatic agent.

To assess the quality of ps laser incisions, a primary fibrotic anterior lens capsule obtained by means of continuous curvilinear capsulorhexis during a cataract operation was used. The capsule was stretched over a metal frame and cut with the ps laser, using the same variable as for the clinical capsulotomies. The stretched specimen was immediately fixed in glutaraldehyde, critical point dried for scanning electron microscopy (SEM), and sputter coated with gold.

Results

IRIDECTOMY

A total of 53 iridectomies were performed with the ps laser (Fig 1, Table 1). During laser treatment, the trabecula of the iris stroma were not just torn apart as in a ns laser iridotomy, but completely removed within the diameter of the applied spiral pattern and dispersed as fine tissue debris into the anterior chamber. We therefore use the term "iridectomy" rather than iridotomy. No iris pigment defect was noted on either side of the iris canal. Compared with ns pulses an increased number of small gas bubbles resulted from the ps laser application and collected in the upper anterior chamber. They were, however, absorbed within 15 minutes after the procedure. No biomiocroscopic change of the superior corneal endothelium or stroma was noted on the first day after surgery under slit lamp examination. In order to prevent the gas bubbles produced by the first laser pulses from covering the application site, the iridectomies were carried out in the 10 or 2 o'clock position.

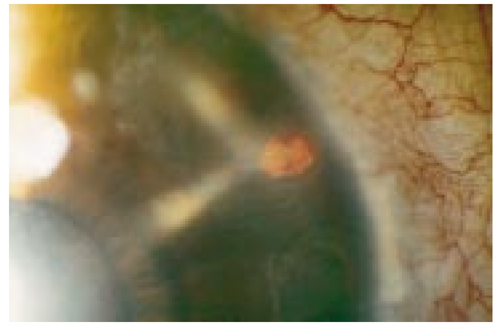

Figure 1 Picosecond laser iridectomy produced with a spiral pattern of 500 µm diameter. Indirect illumination. The iris canal is clearly defined and no adjacent pigment epithelial defect is detectable.

The diameter of the spiral pattern applied ranged between 400 and 1000 µm. The data for 500 µm, 600 µm, and 750 µm diameters are listed separately in Table 1. In 98% of the cases, outflow of pigment through the iridectomy was observed as a sign of primary success. Only in one patient gas bubbles resulting from the laser application were caught between iris and cornea and prevented an effective laser application. In two other patients the iridectomy was thought to be patent due to initial pigment outflow, but when an obscuring iris bleeding had cleared the next day it was revealed not to be so. Three patent iridectomies were not placed close enough to the iris base and were enlarged towards the periphery so that, in total, six iridectomies (11%) required a second laser treatment.

Bleeding from the iris defect occurred in 32 cases (64%) during laser application. All haemorrhages stopped spontaneously within 2 minutes and no recurrent bleeding or hyphaema was observed postoperatively. The incidence of haemorrhages was lower for 500 µm iridectomies (n=4; 44%) than for

Table 1 Comparison of nanosecond laser and picosecond laser iridotomyectomy

		Nd:YLF ps laser			
Iridotomy/iridectomy	*Nd:YAG ns laser*	*All iridectomies*	*500 µm*	*600 µm*	*750 µm*
Number of cases	20	53	9	18	19
Single pulse energy (mJ)	7.9 (6.6–12.0)	0.25	0.25	0.25	0.25
Total number of pulses	6.4 (3–14)	14 851 (1259–60 400)	6668 (1259–19 549)	17 272 (2175–38 729)	16 106 (1870–38 729)
Total energy (mJ)	52 (20–122)	4028 (316–15 400)	1667 (316–4887)	5166 (544–10 975)	4087 (468–9682)
Complications:					
iris bleeding	10 (50%)	32 (64%)	4 (44%)	14 (75%)	14 (74%)
increase in IOP >10 mm Hg	1 (5%)	11 (22%)	0 (0%)	1 (6%)	8 (42%)
increase in IOP >20 mm Hg	0 (0%)	6 (11%)	0 (0%)	0 (0%)	4 (21%)
mean mm Hg increase in IOP	6 (0–21)	9 (0–29)	3 (0–6)	5 (1–14)	16 (1–29)
exudation of fibrin	2 (10%)	1 (2%)	0 (0%)	0 (0%)	1 (5%)
corneal lesion	1 (5%)	7 (13%)	0 (0%)	4 (22%)	3 (14%)
repeat treatment necessary	5 (25%)	6 (11%)	1 (11%)	2 (11%)	3 (14%)

600 µm (n=12; 75%) and 750 µm iridectomies (n=14; 74%). The average rise of intraocular pressure (IOP) as well as the incidence of postoperative IOP spikes of more than 10 mm Hg increased with the size of the iridectomy (Table 1). The IOP rise did not depend on the occurrence of an iris haemorrhage. No lasting increase in the IOP resulted. In seven patients laser effects were inadvertently placed in the posterior corneal stroma, either due to a very shallow anterior chamber or because the patient moved his head. The intrastromal gas bubbles were absorbed within 30 minutes and no change in corneal topography was noted. In one case with repeated laser application, a focal clouding of the crystalline lens below the iridectomy was noted. All patients described the procedure as virtually painless. Patients who had experienced Nd:YAG laser treatment on the fellow eye described the ps laser treatment as less unpleasant. Iridectomies performed with the ps laser generally required considerably more energy than the ns iridotomies (Table 1), but the complication rate was not higher. Retreatment was required more frequently with the ns laser (25%) than with the ps laser.

PUPILLOPLASTY

In two patients a ps laser pupilloplasty was performed to widen a pupillary phimosis after iris suturing in order to facilitate a subsequent retinal argon laser coagulation (Fig 2). By applying pulses of 250 µJ in line patterns of 1 mm length, a considerable dilatation of the pupil could be achieved. The number of pulses was 6150 and 38 000, respectively. In both cases iris bleeding occurred intraoperatively but stopped spontaneously.

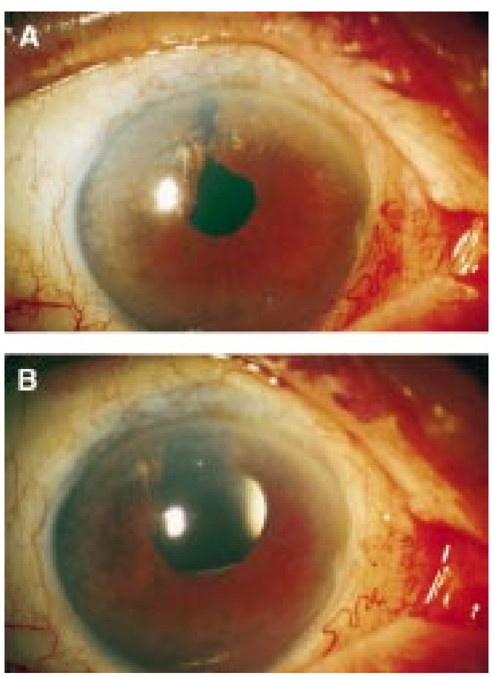

Figure 2 Reopening of a former iris suture to facilitate a retinal argon laser coagulation for diabetic maculopathy (A) preoperatively, (B) 1 day after ps laser iridotomy. Length of cut 1 mm.

CAPSULOTOMY

We used the ps laser for pseudophakic patients to dissect massively fibrotic posterior (n=3) or anterior (n=4) capsules occluding the optical axis in cases where the success of a ns laser treatment appeared questionable. As the ps laser allowed maximally 2 mm long cuts, we combined several line patterns at different angles to produce a polygonal capsulotomy (Fig 3). In all cases, a capsular opening could be created, and the excised piece dropped into the vitreous body or the anterior chamber. In one case it adhered to the IOL and had to be detached by means of two 1.2 mJ ns laser pulses. On average, 690 mJ were required to cut 1 mm of fibrotic capsule (Table 2). The need for repeated reprogramming of the line pattern extended the surgical time to about 15 minutes. Despite a programmed 50 µm safety distance between aiming laser and ps laser IOL damage in the form of superficial lines resulted in all patients (Fig 3C). However, owing to the paracentral application of the laser pulses,

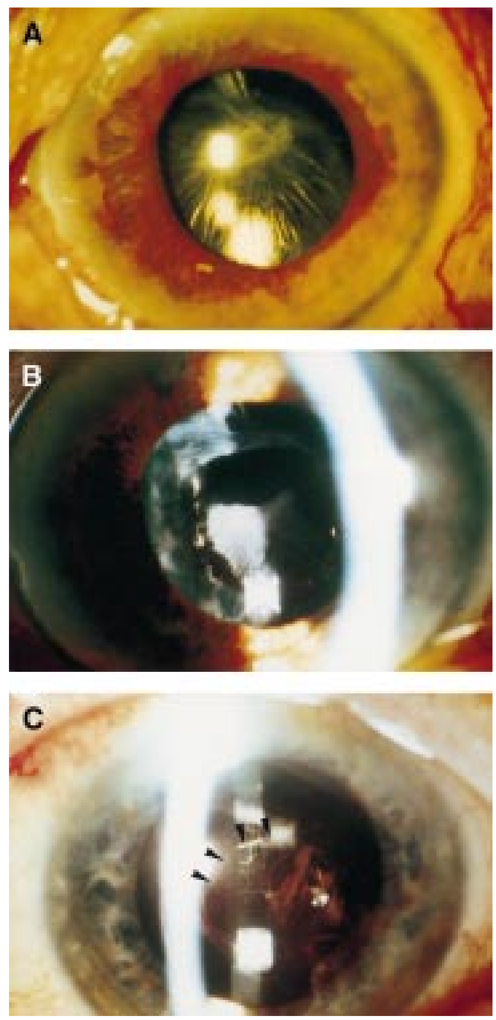

Figure 3 Picosecond laser capsulotomy of a massively fibrosed and phimotic anterior lens capsule (A) preoperatively, (B) postoperatively. The capsule was opened with eight 2 mm long line patterns. Postoperatively, the excised piece of the fibrotic anterior capsule sank down and the optic axis was uncovered. Corresponding with the application pattern, linear IOL defects can be seen in (C) (arrowheads). These defects did not disturb the patient's vision because of their mid peripheral location.

Table 2 Comparison of nanosecond laser and picosecond laser capsulotomy

Capsulotomy	*Nd:YAG ns laser*	*Nd:YLF ps laser*
Number of cases	10	9
Single pulse energy (mJ)	2.05 (1.8–2.5)	0.25
Total number of pulses	29 (11–68)	70 700 (14 800–200 000)
Total energy (mJ)	59 (22–129)	15 155 (3700–50 000)
Complications:		
IOL damage	punctual pits	linear pits
increase in IOP	1	2
corneal lesion	0	0
repeat treatment necessary	0	2

these lines did not disturb the visual performance of the patients. At 200 Hz repetition rate, the laser beam could be directed more precisely than at 1000 Hz, which led to considerably reduced IOL damage. Visibility during surgery was sometimes impaired by gas bubbles caught between posterior capsule and IOL. In one case, it was necessary to wait for their absorption in order to complete the capsulotomy on the following day.

For posterior capsulotomies using the ns laser considerably less total energy was required than with the ps laser, because the plasma produced tissue defects were enlarged by the disruptive forces of the ns pulses. Small IOL pits occurred in six cases, without impairing the patient's visual acuity. The edges of the ns laser capsulotomies were ragged, whereas they were quite smooth with the ps laser, as demonstrated in Figure 4A. Nevertheless they showed some radial tears which are not observed after a continuous curvilinear capsulorhexis (Fig 4B).

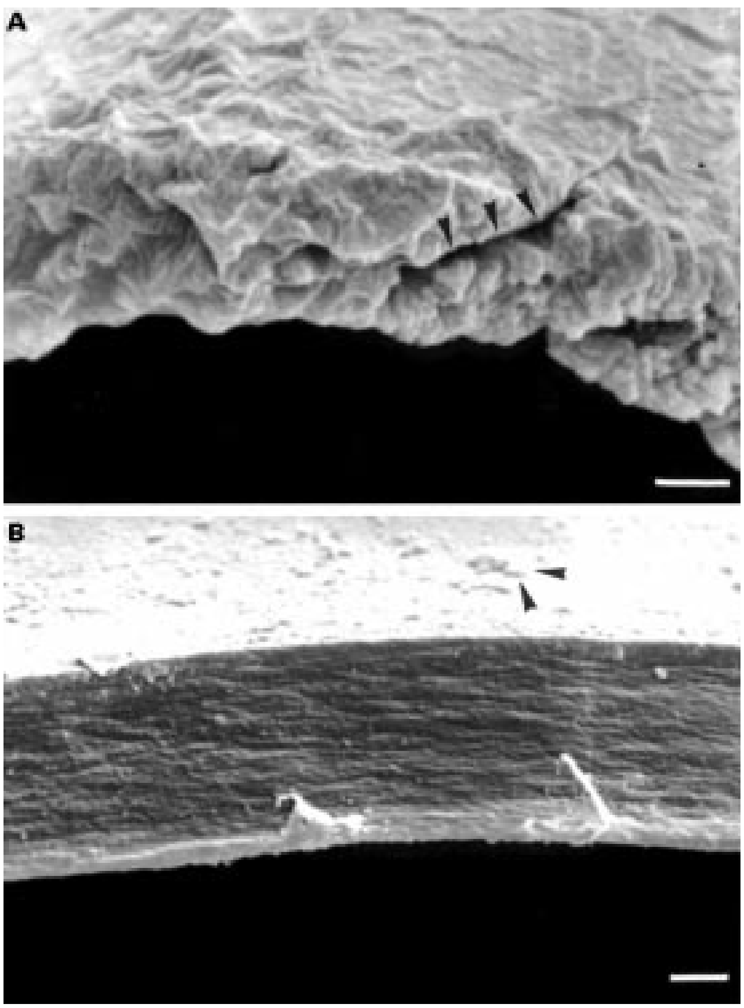

Figure 4 Scanning electron microscopical image of (A) a ps laser capsulotomy, and (B) the edge of a continuous curvilinear capsulorhexis. The fibrous structure of the capsule is visible in (B); Arrowheads in (B) indicate remnants of lens epithelial cells. After capsulotomy with the ps laser, the edge of the same capsule is more irregular, the fibrous structure cannot be seen (A). Radially oriented defects (arrowheads in (A)) appear. Bar = 4 μm.

SYNECHIOLYSIS

Three anterior and posterior iris synechiae were cut without complications using short line patterns (1 mm). Pulse energies of 140–300 μJ were employed, and the total energy amounted to 185, 324, and 566 mJ respectively.

VITREORETINAL INDICATIONS

Vitreoretinal surgery in the fundus periphery was attempted in three cases. We tried to dissect vitreoretinal fibrotic adhesions (n=2) and to perform a peripheral retinotomy (n=1) near the equator of the globe. Despite clear refractive media and aphakia (two cases) this proved to be impossible even at the maximum possible single pulse energy of 400 μJ.

Discussion

A number of previous in vitro investigations provided evidence for the increased precision of the ps laser in comparison with ns laser pulses.[9 12] Our clinical experience shows that these microdisruptions can be used effectively for standard Nd:YAG laser indications if series of computer controlled pulse patterns are employed and that even highly fibrotic tissue can be dissected effectively. The low energy of the individual pulses minimises the danger of damaging adjacent structures, as is demonstrated by the lack of collateral pigment defects in iridectomies. It may therefore be assumed that known complications of capsulotomies such as retinal detachment, cystoid macular oedema,[13] or focal endothelial and trabecular damage[14 15] may be reduced when using the ps laser.

IRIDECTOMY

Basal iridectomies were easier to perform with the ps laser than with the ns laser. With ns laser pulses, the iris trabecula are ruptured and retract providing an iridotomy canal of a rather small diameter (<200 μm).[16] Fibrin exudation often leads to a reclosure of the defect at a later time.[17 18] Nanosecond laser iridotomies produced with pulse energies of several mJ often show a large defect of the pigment epithelium surrounding the small iris defect which is created by the disruptive action of plasma expansion. Picosecond iridectomy has the advantage that a larger and more clearly defined iris canal can be produced while the adjacent pigment epithelium remains intact. However, the dispersion of cellular debris or iris bleeding into the anterior chamber and its accumulation in the inferior chamber angle may compromise the trabecular outflow facility and probably contributes to the transient increase of IOP observed with iridectomy diameters of 600 and 750 μm. The occurrence of severe postoperative IOP spikes—which is well known from Nd:YAG laser iridotomies[19]—correlated with the size of the ps iridectomy because an increase of the pattern diameter from 500 to 750 µm results in a 2.25-fold increase of the volume of dispersed iris tissue. However, no lasting increase of IOP was observed in our patients. Minor intraoperative iris bleeding was more frequent following ps iridectomies (65%) than after ns iridotomies (50%). No hyphaema was observed on the first postoperative day as sometimes is reported after ns iridotomies.[20] The incidence of iris haemorrhages was larger for 750 compared with 500 µm sized ps iridectomies, owing to the increased probability of hitting an iris vessel with the increased pattern size. Focal lens damage which was noted in one out of 53 patients is also known from ns laser iridotomies.[21] A diameter of 500 µm seems optimally suited to achieve iridectomies of a considerable size while avoiding transient pressure spikes and haemorrhages. Larger patterns are also more likely to produce corneal effects.

CAPSULOTOMY

Series of ps laser pulses were used to cut massively fibrotic lens capsules in cases where the ns laser is ineffective or bears the risk of producing damage to adjacent tissue structures owing to its more disruptive nature. However, despite of the less disruptive effect of the ps laser, pulse series application was accompanied by a high incidence of IOL damage. Inadvertent defocusing of the laser beam leads to more severe lens damage when ps pulse series are applied than with the application of single ns pulses, even though the energy of the individual ps pulses is lower than the energy of ns pulses. The risk of lens damage is particularly high when linear incisions are employed in the presence of a curvilinear lenticular surface. It may endanger the visual function of the patient if it occurs centrally.[22] Use of very short line patterns for each individual incision would reduce the damage risk but extensively increase the treatment time. Lower pulse repetition rates (200 Hz) give the surgeon improved control of the laser application and reduce, but do not exclude, the danger of IOL damage. With ns pulses, the focus can be placed slightly behind the posterior lens capsule, to protect the IOL, because the capsule is still torn apart by the disruptive mechanical forces caused by the expanding laser plasma. This strategy is not possible with ps pulses, where the surgical effects rely on the tissue evaporation by the laser plasma itself. We therefore applied the ps pulses always at some distance from the optical axis in the shape of a hexagon around the IOL centre. In our opinion, this procedure is only advantageous for extreme capsular fibrosis, where the ns laser is either ineffective or where retinal complications are more likely to occur owing to the high disruptive forces of ns pulses. For "standard" capsulotomies without extensive tissue fibrosis, the ns Nd:YAG laser seems to be more suitable than the ps laser tested here.

A procedure where the good cutting properties of the ps laser may be advantageous is anterior capsulotomy immediately before cataract surgery. This procedure would avoid the mechanical stress on the zonular fibres exerted during capsulorhexis. We did not test this application in the present study, because the largest ring pattern available with the ISL 2001 laser system had a diameter of only 2 mm which is too small even for a foldable IOL implant. The follow up design of the laser, model 4001, provides pattern diameters of up to 6 mm, which means that larger capsulotomies can be performed without reprogramming. However, our SEM investigations of the capsular surface after a ps laser cut showed that the edges of the laser cut were not as smooth as the edge of a continuous curvilinear capsulorhexis. The small radial tears observed in the laser cut could provide starting points for the formation of larger tears during phacoemulsification or insertion of the IOL.

VITREORETINAL APPLICATIONS

Picosecond pulse series remained ineffective for treatment of pathologies in the peripheral vitreoretinal area, even when the maximum pulse energy was applied (400 µJ). We observed a distortion of the aiming laser focus, and we assume that the corresponding astigmatic distortion of the ps laser focus, as a result of the oblique access through the contact lens and the crystalline lens, was so strong that the threshold for plasma formation could not be exceeded. Moreover, vignetting occurred in the three mirror lens because of the large focusing angle of 20° which is larger than that of conventional Nd:YAG lasers (12–18°). Problems caused by aberrations could be overcome by restricting the vitreoretinal laser applications to the central part of the fundus where few aberrations occur and by the use of more appropriate contact lenses. Vignetting would be less if a smaller focusing angle would be available for vitreoretinal applications. A previous study showed that central retinotomies can be performed effectively on enucleated eyes,[9] and the ps laser has already been applied successfully for patient treatments in the central, anterior, and medial vitreous body (V Marchi, personal communication).

Conclusion

Picosecond pulses have a more clearly defined and spatially more confined effect than ns pulses because of their lower pulse energy. The lower pulse energy, on the other hand, results in the necessity to apply series of pulses with high repetition rates to achieve a surgical effect. As a consequence, the total pulse energy required with the ps laser was always higher than that used with the ns laser for similar indications. The higher total energy did not lead to a higher complication rate. In capsulotomies, the application of ps pulse series led to a higher incidence of extended IOL damage than observed with single ns pulses. Iridectomies could, however, be performed very well with series of ps pulses applied in a spiral pattern. At present, we do not consider the spectrum of intraocular photodisruption to be considerably broadened by the Nd:YLF ps laser. Improvements in the laser application system—for example, a variable focusing angle and energies of up to 1 mJ, which would be advantageous for vitreoretinal applications in the fundus periphery—are necessary to make full use of the advantages of ps pulses.

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