13 Lamellar Corneal Resection with LDV Crystal Line Femtosecond Laser after Penetrating Keratoplasty

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Chapter Outline

- Physics and technical approach
- Minimizing energy—maximizing cutting precision
- Technical Realization and clinical outcomes
- Patients and methods
- Results
- Discussion

PURPOSE

The purpose of this study is to describe the underlying physics of the crystal line LDV femtosecond laser (Ziemer ophthalmic systems AG, Port, Switzerland), and to demonstrate the capability of this device to perfom flap resections in postkeratoplasty corneas through scarred tissue.

INTRODUCTION

As several different models of femtosecond (fs) laser systems have become available, refractive and corneal surgeons-strive to perform all types of corneal surgery with "all-laser" procedures. Particularly, performing corneal resections through scarred tissue, as encountered in eyes that have undergone perforating keratoplasty (PKP), has remained a challenge.

As the trend in refractive and corneal surgery is moving towards all-laser-treatments, there are now different fs-laser systems for applications in corneal surgery available. All current fs-laser systems use short laser pulses to dissect corneal tissue by photodisruption. However, there are significant differences in technical detail and in clinical outcome between different devices.

PHYSICS AND TECHNICAL APPROACH

Laser—Tissue Interaction

The interaction process of all fs-laser systems for corneal surgery, e.g. preparation of corneal lenticule in LASIK procedures, is based on nonlinear absorption and consecutive disruption of the tissue, followed by formation of a cavitation bubble and a residual gas bubble. Nonlinear in contrast to linear absorption means that the tissue is transparent for the infrared laser radiation at moderate intensities, hence no absorption occurs. Only at very high intensities, which can be achieved by compressing the laser pulse in time (ultrashort) and in space (strong focusing), some photons can be absorbed co-instantaneously by the tissue. The narrowness of the region of photodisruption depends on the degree to which the beam is strongly focused and is never, in practice, a single point in z-axial space. However, nonlinear interaction gives the user the advantage of three dimensional tissue processing. The absorption process is not limited to the surface anymore.[1-4]

While photodisruption scales with pulse intensity (W/cm^2), the unwanted side-effects such as thermal heating, stress- and shockwaves, or large residual gas bubbles, scale with pulse energy (J). It is therefore desirable to minimize pulse energy while keeping the pulse intensity above the photodisruption threshold level (Fig. 13.1). Two obvious principles can be used for optimizing pulse intensity at reduced pulse energy: Compression in the time domain (pulse shortening) and in the spatial domain (strong focussing).

MINIMIZING ENERGY—MAXIMIZING CUTTING PRECISION

Shortening the pulse duration is a basic physical challenge, which is related to the spectral bandwidth of the laser medium. The pulse duration of typical fs-laser systems is around 200 to 800 fs (1 fs = 10^{-15} sec). In this range, the energy threshold for optical breakdown increases almost linearly with pulse duration (Fig. 13.2). Thus, the shorter pulse duration of Ziemer's Femto LDV (approx. 250 fs) is related to a lower pulse energy threshold than other systems, which operate at pulse widths approx. 600 to 800 fs.

The second way to decrease the energy is to decrease the focal volume of the laser spot. The focal volume of a Gaussian laser beam depends on the axial extension, the so called Rayleigh range

$$z = \frac{\pi w_0^2}{\lambda}$$

and the beam waist

$$w_0 = \frac{f\lambda}{\pi w_L}$$

where f is the focal length of the focusing lens, λ the laser wavelength and W_L the radius of the beam at the focussing

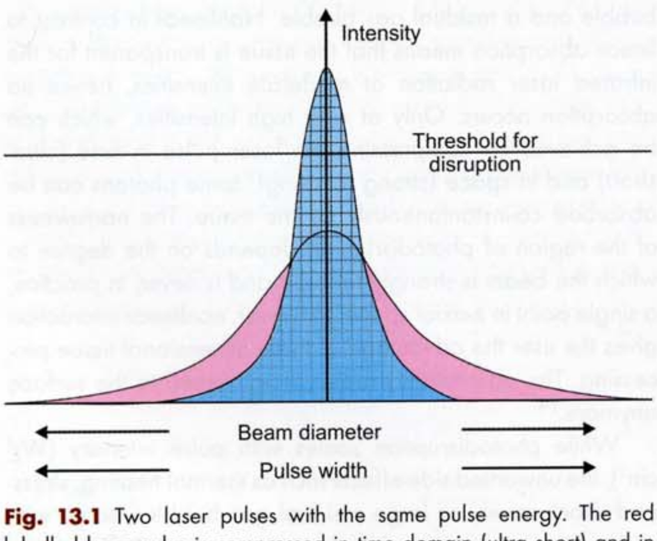


Fig. 13.1 Two laser pulses with the same pulse energy. The red labelled laser pulse is compressed in time domain (ultra short) and in space (strongly focussing with high NA). As a result its intensity increases above threshold for photodisruption

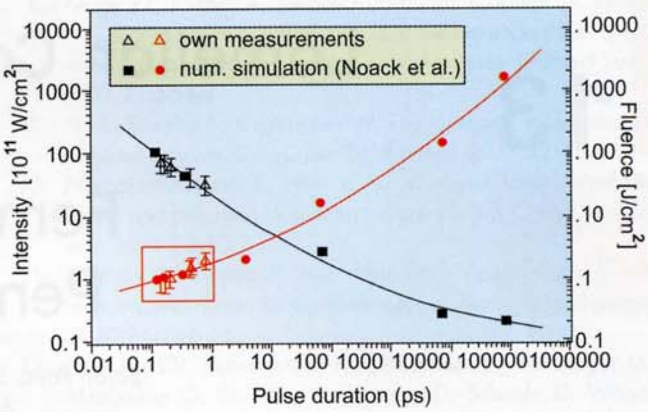


Fig. 13.2 Threshold values for photodisruption in water. The black curve shows the intensity threshold and the red curve represents the fluence of a single laser pulse. In the range of 100 fs to 1 ps (red box) the function of energy threshold is almost linear with pulse duration. [Calculated data points are from Noack[3]]

lens. In other words, the focal volume varies inversely with the fourth power of the numerical aperture

$$NA = \frac{w_L}{f}$$

of the focussing optics. The larger the NA the smaller is the focal spot and finally, the less pulse energy is needed (Fig. 13.3) to cause photodisruption. According to its definition, there are two ways to increase the NA. One possibility is to increase the beam diameter at the focusing optics, which requires large and expensive optical components. As an alternative, one can also decrease the focal length of the focusing lens, which on the other hand reduces the working distance of the laser system (Fig. 13.4). Finally, the laser's repetition rate (laser frequency) has an important influence on the pulse energy threshold. The higher the laser frequency, the less pulse energy is needed (Fig. 13.5). Thus, it is obvious that the Ziemer LDV, which operates at >5 MHz and at large NA, offers a significant advantage over other devices which operate at frequencies in the tens or hundreds of kHz MHz-Laser take advantage of this[5] and at up to 5 times larger focal widths.

TECHNICAL REALIZATION AND CLINICAL OUTCOMES

With respect to the interaction process and the beam delivery, fs surgical lasers can thus be classified into two groups: one group characterized by high pulse energy with low pulse frequency, and the other group characterized by low pulse energy with high pulse frequency. In the "high pulse energy – low pulse frequency" group, amplified laser systems are used to deliver pulse energies in the range of 1 to 5 µJ to the cornea. The typical repetition rate is about some kHz. In contrast,

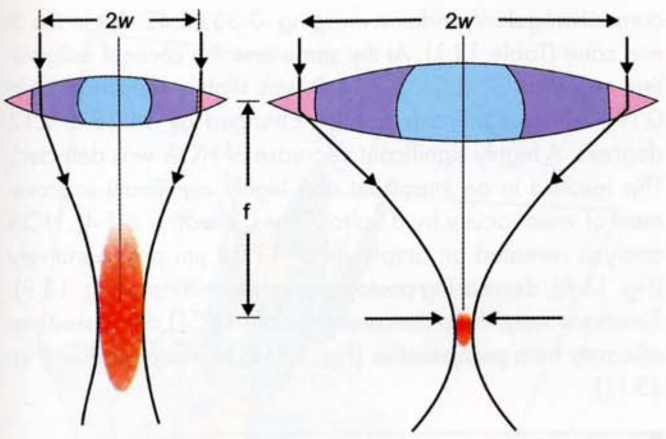


Fig. 13.3 The focal volume of a Gaussian laser beam scales with the numerical aperture NA = W_L/f of the focussing lens. The larger the NA, the smaller is the focal spot volume

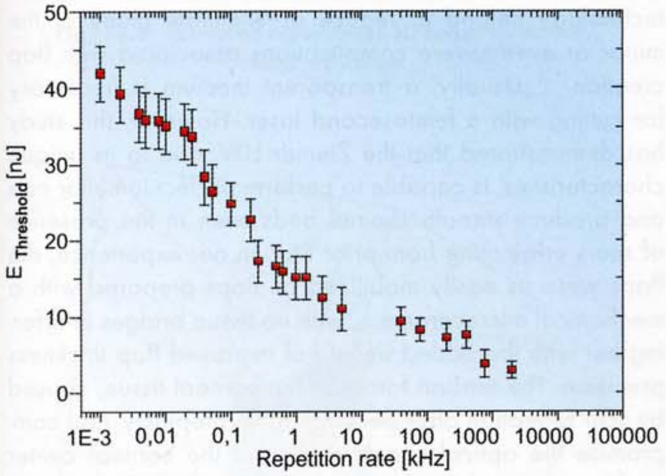


Fig. 13.5 The threshold energy in water decreases with increasing laser frequency. For MHz laser frequencies the threshold is almost half of kHz laser frequencies

the "low pulse energy-high pulse frequency" Contrary to that the Ziemer's Femto LDV, currently the only commercial device in this group, employs short 200 fs pulses, high NA optics and a very high pulse repetition rate exceeding 5 MHz. The required pulse energies in such a design are in the range of a fewless than 100 nJ (nano-Joules) which delivers only nJ pulse energies to the eye and uses MHz repetition rates clearly belongs in the "low pulse energy-high pulse frequency" group. Based on the laser parameters, the physical nature of the cutting processes of the two groups is different. In the "high pulse energy laser group", the cutting process is driven by mechanical forces which are applied by the expanding bubbles and which disrupt the tissue. This cutting process is very efficient because the radius of disrupted tissue is larger

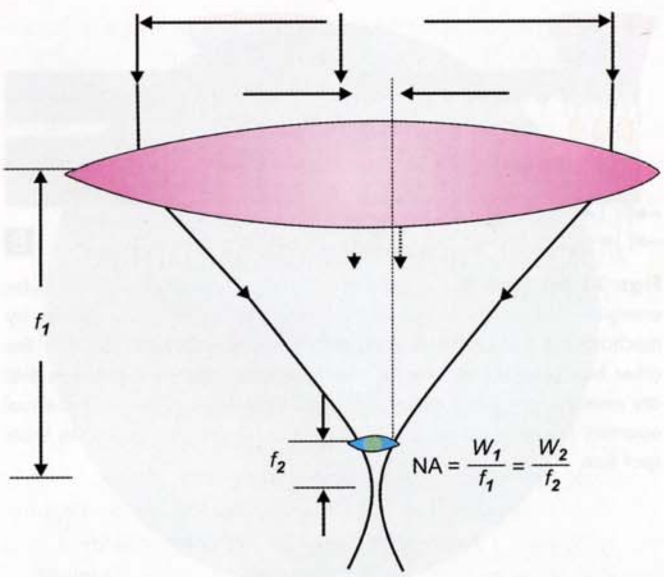
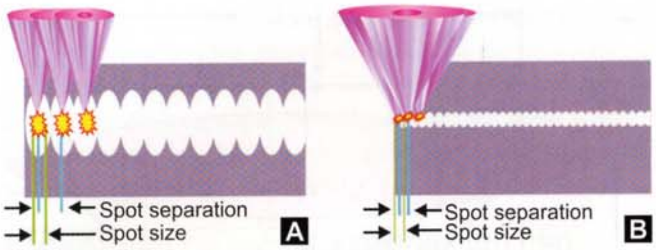


Fig. 13.4 At a constant relationship of focal length and lens diameter, a given focal diameter of the laser beam can be achieved by either large lenses and long working distances or by smaller lenses with shorter working distances

than the laser spot itself. Hence, the spot separation of the scanned laser pulses can be larger than the spot diameter (Fig. 13.6A). On the other hand, due to the lower focusing accuracy and the larger remaining gas bubbles, poorer flap qualities, OBL (opaque bubble layer), TLS (transient light sensitivity syndrome) and anterior chamber bubbles may appear. There can be an additional waiting time for the proper use of the Excimer's eye tracking system as well. Using low pulse energies, the cutting tissue disruption process is confined by to the focal spot size of the laser pulse. In fact, the actual photon interaction volume can be even smaller than the focal volume due to the nonlinear intraction requiring a certain threshold for disruption to occur. As a consequence, more pulses are needed to cut the same area. To keep the total operation procedure time at the same level, higher pulse repetition rates are required (Fig. 13.6B). Since a pure fs-laser oscillator is used, it delivers these many pulses as well as very high stability and robustness against environmental influences compared to amplifier systems. The clinical outcome shows a perfect cut even through scars.

PATIENTS AND METHODS

Nine eyes that had undergone penetrating keratoplasty 1-3 months earlier were selected to undergo lamellar keratectomy (flap creation for subsequent excimer laser ablation) with a Ziemer LDV Crystal line fs-laser (Fig. 13.7). Preoperative characteristics included an astigmatism of more than 4 D, a



Figs 13.6A and B For smaller focusing angles with higher pulse energies (lower laser frequencies), the cutting effect is driven by mechanical forces of the increasing cavitation bubble (B). On the other hand, MHz laser frequencies can offer many more pulses that are needed for cutting with lower pulse energies and larger numerical aperture (B). In this case, the size of the cut is defined just by the focal spot size

Fig. 13.7 Crystal line LDV femtosecond laser

corneal irregularity of more than 4 D in the 5 mm zone and significant higher order aberrations (HOA). The best preoperative visual acuity range was in all cases less than 0.125. A 9.5 mm suction ring, 110 µm flap thickness and manufacturer's standard resommended laser parameters were used in all cases for performing a lamellar LASIK cut. Standard ophthalmological examination, including visual acuity examination, corneal topography and wavefront aberrometry were performed before and 6 weeks after treatment. For purposes of statistical data analysis, the SPSS program was used.

RESULTS

After performing a lamellar keratotomy and repositioning of the corneal flap we observed a significant decrease of the corneal-irregularity-index averaging -0.33±0.42 dpt in the 5 mm zone (Table 13.1). At the same time the corneal astigmatism reduction of -3.01 ± 2.14 D was slightly significant (p = 0.19), whereas the axis position changed by 14.28 ± 2.12 degrees. A highly significant decrease of HOA was detected. This resulted in an important and highly significant improvement of visual acuity by 3 up to 7 lines, (mean 5 ± 1.4). HOA analysis revealed an amplitude of 13.28 µm pre-operatively (Fig. 13.8), decreasing postoperatively to 1.82 µm (Fig. 13.9). Simultaneously, the point-spread function (PSF) decreased significantly from preoperative (Fig. 13.10) to postoperative (Fig. 13.11).

DISCUSSION

This study investigated surgical outcomes obtained by using the Ziemer Crystal line LDV Femtosecond Laser for lamellar keratectomy after PKP. The use of this fs laser technology helped to reduce or eliminate many of the minor or even severe complications associated with flap creation.[7-11] Usually, a transparent medium is necessary for cutting with a femtosecond laser. However, this study has demonstrated that the Ziemer LDV, due to its unique characteristics, is capable to perform perfect lamellar cuts and produce smooth stromal beds even in the presence of scars originating from prior PKP. In our experience, the flaps were as easily mobilized as flaps prepared with a mechanical microceratome, with no tissue bridges interfering but with the added benefit of improved flap thickness precision. The tension forces in the corneal tissue, caused by scar formation after penetrating keratoplasty, can compromise the optical characteristics of the corneal center and hence visual acuity. A lamellar keratotomy in the anterior third of the cornea leads to relevant tissue relaxation, with concomitant decrease of corneal irregularities and aberrations, leading to improved visual acuity and better visual comfort. This treatment can form the basis for subsequent refractive fine-tuning by standard refractive procedures; namely LASIK by performing excimer laser ablation in the stromal bed, by re-lifting the flap created as described in this study.

Table 13.1 Topographical corneal parameters

	MW	SD
Δ corneal-irregularity-index	-0.33	0.42
Δ astigmatism power	-3.01	2.14
Δ astigmatism axis change	14.28	2.12

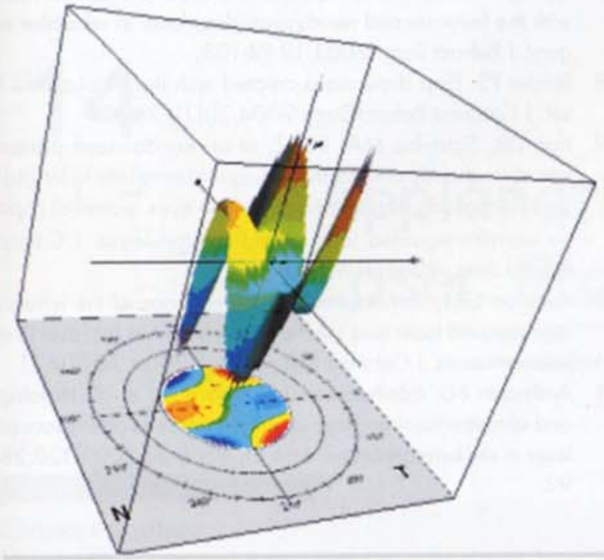


Fig. 13.8 Aberration higher order 3D before keratotomy; ampl: 13.28 μm

Fig. 13.10 Aberration higher order PSF before keratotomy

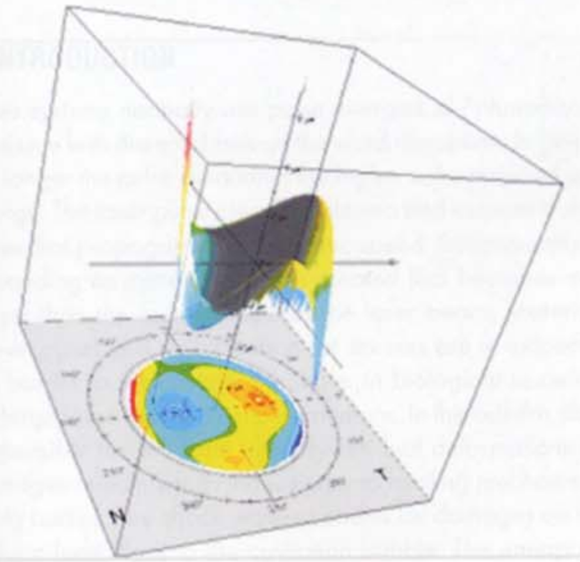


Fig. 13.9 Aberration higher order 3D after keratotomy; ampl: 1.82 μm

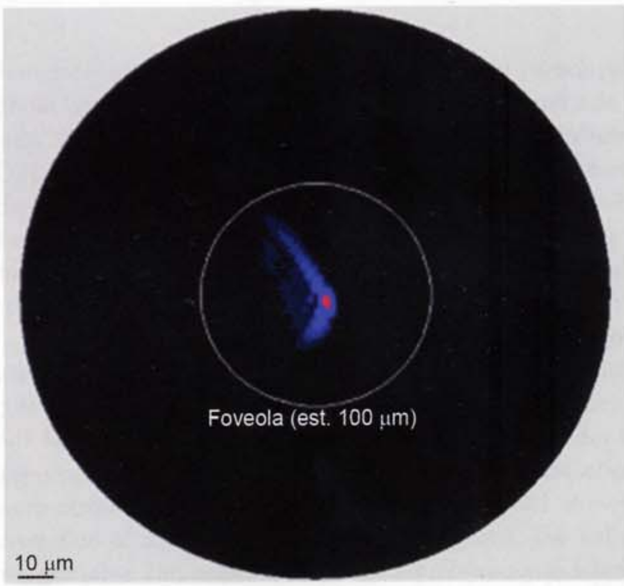


Fig. 13.11 Aberration higher order PSF after keratotomy

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