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Ultrafast Lasers in Ophthalmology

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Invited Paper

Abstract

Ultrafast laser pulses have become a promising tool for microsurgery of the eye. Due to the low energy threshold, side effects are limited to the micrometer range This precision enables the use of ultrashort laser pulses in a broad field of medical applications. Especially, the interaction process based on nonlinear absorption offers the opportunity to process transparent tissue not only on top of a surface but three dimensionally inside the bulk.
This mechanism is used in refractive eye surgery, where fs pulses create flaps into the corneal tissue to remodel the curvature of the eye and to improve visual acuity. Moreover, fs pulses could be used to influence the biomechanics of the crystalline lens of the eye and improve accommodation on eyes who suffer from presbyopia.

Keywords: femtosecond laser pulses; refractive surgery, presbyopia, optical breakdown

1. Photodisruption by optical breakdown

Ultrafast laser systems have successfully entered the refractive surgery market since IntraLase introduced its first commercial system in 2001 as a replacement for the mechanical microkeratome [1]. The interaction process on ultrafast corneal surgery is based on non linear absorption and consecutive disruption of the tissue accompanied with cavitation and a remaining gas bubble. Non linear absorption means that usually the corneal tissue is transparent for the infrared laser radiation at moderate intensities and no absorption takes place. Only at very high intensities, which can be achieved by compressing the laser pulse in time ("ultrafast") and in space (focused with high NA), four or more infrared photons act as one uv photon and are absorbed by the tissue. This multi photon interaction gives the user the advantage of three dimensional tissue processing. The absorption process is not limited to the surface anymore [2-5].

The multi photon absorption process ionizes the tissue and thus generates free electrons. Depending on the pulse duration and the pulse intensity, further free electrons will be generated as an avalanche process. The number of free electrons characterizes the following disruption process. At low pulse energies, only a so-called low density plasma is produced. The cutting process is dominated by photochemically induced decomposition of the tissue and thermoelastic disruption. At higher pulse energies a luminescent plasma is generated. This process is called plasma mediated ablation, due to the explosive expansion of the plasma.

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Mechanical rupture and transient cavitation as well as remaining gas bubbles are typical side effects for this process. In order to achieve maximum precision of the cut and minimize the collateral damage, one has to minimize the energy threshold for optical breakdown by shortening the pulse duration and minimizing the focal spot volume Shortening the pulse duration is a basic physical problem, which is related to the spectral bandwidth of the laser medium. Titanium Sapphire Lasers, for example, have the broadest spectrum and the shortest (< 100 fs) pulses, however they are very complex in their setup and relatively expensive. Yb-doped fiber lasers or solid state lasers

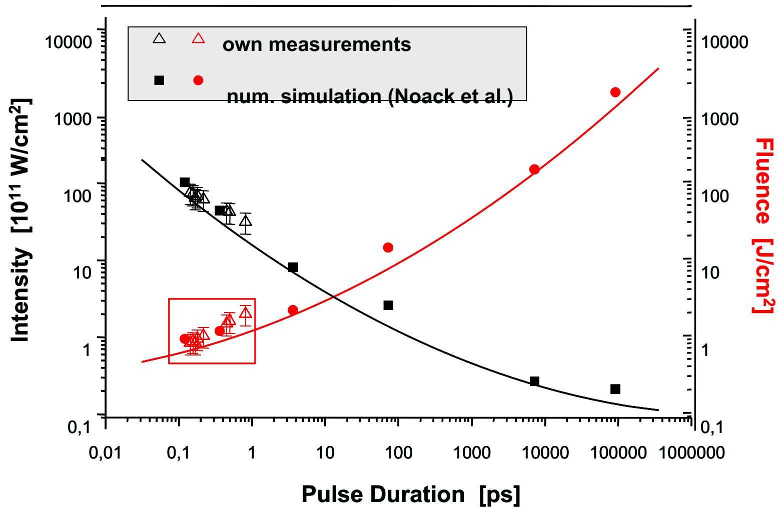

Fig. 1. Threshold values for photodisruption in water. The black curve shows the Intensity threshold and the red curve represents the fluence of a single laser pulse. In the range of 100 fs to 1 ps (red box) the function of energy threshold is almost linear with pulse duration. Calculated data points are from [Noa 99]

which emit around 1000 nm wavelength are today the most reliable systems and also the cheapest way to produce ultra short pulses. Their pulse duration is typically around 200 to 800 fs. In this range the energy threshold for optical breakdown increases almost linearly with pulse duration (Fig. 1).

2. Refractive Corneal Surgery

The principle of conventional refractive corneal laser Surgery (**La**ser in **Si**tu **K**eratomileusis, LASIK) is shown in Fig. 2 In a first step, a lamellar intrastromal cut is performed by a mechanical cut of a microkeratome (mechanical knife). In a second step, the anterior flap of the cornea is lifted and an excimer laser (193 nm) remodels the radius of curvature of the cornea depending on the refractive error of the treated eye. Finally, the flap will be repositioned on

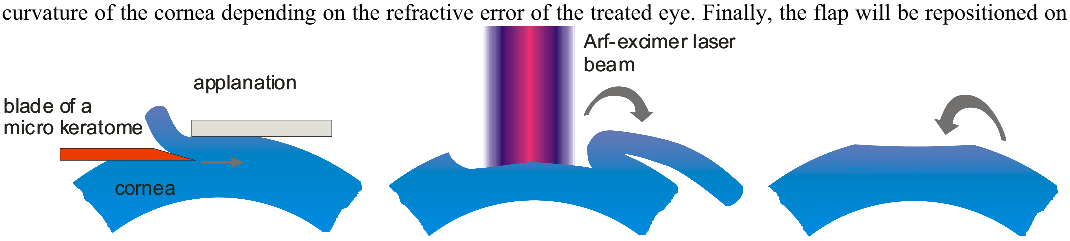

Fig. 2. Principle of the LASIK procedure

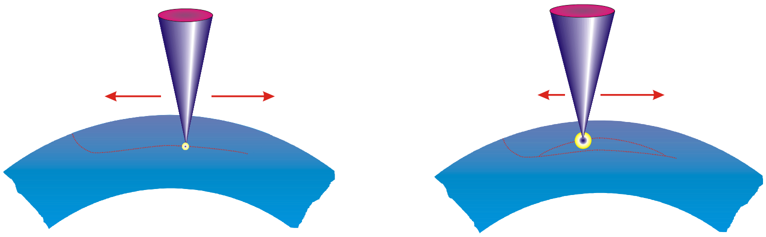

Fig. 3. fs-LASIK: the mechanical microtome is preplaced by an ultrafast laser (left). FLEX-procedure: the mechanical microtome and the excimer laser as well is replaced by the femtosecond laser (right)

the cornea. The surface of the cornea follows the removed volume of the excimer laser, thereby leading to a change in refractive power.

In 1998 Tibor Juhasz and his group has replaced the mechanical microkeratome for the first time by using an ultrafast laser [6] and rrecently, a procedure, called FLEX (**F**emtosecond **L**enticule **Ex**traction) was introduced by Carl Zeiss Meditec were the second step to remove corneal tissue with an excimer laser is also replaced by the ultrafast laser. In this procedure, another cut prepares a stromal lenticule with the desired shape, depending on the refractive error of the treated eye (Fig. 3).

3. Femtosecond-Lentotomy

Presbyopia is an age related effect every human is suffering beginning at the age of about 45 years. Reading glasses are the conventional treatment so far. According to the Helmholtz theory the loss of accommodation in age is due to the hardening and the resulting loss of elasticity of the crystalline lens. However the ciliary muscle and the lens capsule stay active, respectively. Therefore a possible treatment concept is to regain the flexibility by inducing sliding planes in form of microcuts inside the crystalline lens.

Myers and Krueger were the first who described the clinical prospect of deeper delivery inside the eye, and proposed the treatment of the crystalline lens by using the mechanism of photodisruption. They have created intralenticular incisions with a 500 nanosecond laser to soften the lens tissue and re-establish its flexibility [7,8]. In further investigations of the treatment of the crystalline lens, Ripken et al. showed that cutting different pattern inside the lens tissue with femtosecond laser pulses (“fs-lentotomy”) increased the flexibility of the lens, since the cutting pattern act as gliding planes for the hardened lens tissue. Moreover, the flexibility of the lens was increased depending on the particular cutting pattern [9,10].

In a recent study, 10-week-old rabbits underwent lentotomy with a 100-kHz femtosecond laser. A 3-D scanning device was used to deliver 300 fs pulses with a central wavelength of 1,041 nm. The eyes fixed to the scanning device by the suction ring while the cornea was applanated by the flat glass contact (Fig. 4), enabling intralenticular laser pulse scanning with a resolution of 1 µm. The intralenticular laser cutting pattern was a combination of radial and annular layers. The pulse energy, which was varied between 1.2 and 1.6 µJ, was separated between 6 and 7 µm in the x-y plane and 50 µm along the optical axis. With the high repetition rate, the total laser treatment lasted 25 seconds.

Follow-up was performed up to six months postsurgery. No hazardous side effects to the cornea and the lens capsule were observed. Photodisruption inside the lens tissue leads to small gas-filled bubbles, which remain as small, faint opacities after the bubbles disappear. The gas bubbles vanish because the gaseous content of the bubbles dissolves.

OCT images taken prior to the laser treatment provide essential information

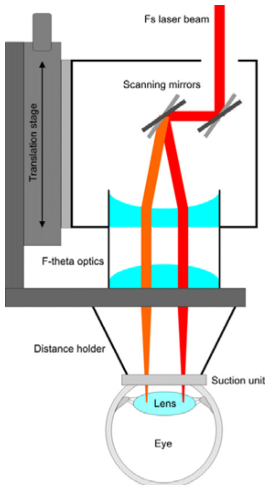

Fig. 4. fs-Lentotomy: the eye is fixed to the scanning device while the cornea is applanated

for targeting the appropriate depth at which to place the cutting pattern. Images taken immediately after the laser surgery verified that the cut was placed, as intended, well below the lens capsule. Therefore, OCT localization plays an integral and essential part in the feedback of any intralenticular laser treatment.

During six month follow-up, the cutting pattern appear well localized and less intense. Actual cataract formation, which would be visible as a progressive opacity that increases light scattering and spreading into the surrounding tissue, was not observed. Later cataract formation, beyond the first six months, seems unlikely. Allthough these first results on treating presbyopia with fs-laser pulses are very promising, more in vivo studies in regard to long-term cataract formation and increase of accommodative amplitude are necessary to transfer this treatment concept into a successful clinical method for restoring accommodation.

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