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Femtosecond laser in ophthalmology – A short overview of current applications

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Abstract

Ultrafast lasers, such as the femtosecond (fs) laser, are being increasingly used in ophthalmology, thus allowing a wide variety of applications in refractive surgery. In the future, their use may also be further extended to include cataract, glaucoma, and retinal surgery. The fs laser first appeared in ophthalmology in 2001 and it continues to grow in popularity. Its main uses include LASIK, penetrating keratoplasty, and presbyopia correction all of which will be discussed in this paper.

Keywords: Femtosecond laser; Refractive surgery; Laser *in situ* keratomileusis; Keratoplasty; Cataract surgery

Introduction

In addition to the nanosecond (ns) and picosecond (ps) lasers used in ophthalmology, a relatively new laser technology is becoming popular for use in refractive correction. The ultrashort laser pulses of the femtosecond (fs) laser, which focuses the laser beam to a spot size of several micrometers in diameter and does not exceed a pulse energy of 1 μJ [1], are in the range of 100–200 fs pulse duration. What is unique about the fs laser is its ability to produce a cut within the corneal stroma, rendering the need for a microkeratome unnecessary. Recently, the fs laser has been increasingly used for presbyopia treatment as well as for corneal refractive corrections, including laser *in situ* keratomileusis (LASIK), presbyopia correction, and penetrating keratoplasty (PKP).

Femtosecond lasers have ultrashort laser pulses which means that the pulse energy is decreased and that there is a reduction in the amount of thermal and mechanical damage to the surrounding corneal and stromal tissue. In a study by Lubatschowski et al. [1], minimal mechanical or thermal damage was seen in the adjacent tissue of the order of ≤1 μm within the area of fs laser application. The investigators concluded that the damage was comparable to that produced by an ArF excimer laser ablation.

The first commercially available fs laser model, the IntraLase FS laser (Abbott Medical Optics Inc., Santa Ana, CA, USA), was introduced in 2001 [2]. The technology was marketed as a replacement for the mechanical microkeratome [3]. Since then other fs lasers, including the Femtec (Technolas Perfect Vision, Heidelberg, Germany), Femto LDV (Ziemer Ophthalmic Systems, Port, Switzerland), and the VisuMax (Carl Zeiss Meditec AG, Jena, Germany), have entered the market [2]. Although each system boasts its own unique features and offers various configurations [2], all fs lasers have the same interaction process based on nonlinear absorption and tissue disruption [4]. They allow three-dimensional tissue processing and absorption beneath the corneal surface [5–7]. Systems either offer high-pulse energy and low-pulse frequency, applying pulse energies of approximately 1 μJ to the cornea, or low-pulse energy and high-pulse frequency, which applies pulse energies in the nJ range. During cutting with low-pulse energy, tissue decompensation and thermoelastic disruption is photochemically induced, whereas with high-pulse energy, plasma-mediated

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ablation as well as mechanical rupture and transient cavitation bubbles occur [4]. In the latter, the cutting process utilizes mechanical forces.

Gas bubbles and transient cavitation are two side effects of high-pulse fs energy. However, this technology offers many advantages for refractive correction, including precise cuts and minimal complications. Once designed as a simple flap cutter for refractive surgery, the fs laser is being used in new and exciting applications, including preparing cuts for intrastromal corneal ring segments, lamellar keratoplasty, and presbyopia correction.

Laser *in situ* keratomileusis

Using the fs laser to create a flap prior to LASIK has become established as a standard procedure. Between 2006 and 2007, the number of fs-created flaps during LASIK more than doubled, with 15–17% of surgeons changing over from the mechanical microkeratome to the fs laser [8].

Its use eliminates most of the complications associated with microkeratome-created flaps including variable flap thickness and reduction of mechanical and thermal side effects [9–11]. Application of the fs laser to the corneal stroma, focussing the ultrashort laser pulses underneath the surface and inside the transparent materials, achieves a smooth and standardized cut [6,12].

Preparing corneal flaps with a mechanical microkeratome may produce variability; however, more standard flaps are possible with the fs laser. In an early fs study performed by Heisterkamp et al. [13], investigators created the fs flap cut at an angle of 60° to avoid difficulties with the opening of the flap. They found no significant wound healing reaction inside the corneal stroma and no proliferation of epithelial cells. Several minutes after flap reposition, the cornea was almost transparent. No wound healing reaction was noted.

Another advantage of using the fs laser to create a flap is the ability to cut thin flaps. Currently it is possible to cut flaps as thin as 90–100 μm [14]. This modified technique is known as sub-Bowman's keratomileusis. Additionally, as an acceptable alternative to LASIK, photorefractive keratectomy (PRK) provides better biomechanical stability [15]. Using the fs laser to create the flap is also advantageous because of the increased biomechanical stability.

Presbyopia correction

One of the most recent developments in the ophthalmologic application of fs lasers is its use in the correction of presbyopia. Previously, the only successful methods for presbyopic correction included lens implants or monovision surgery. However, Ripken et al. [16] studied the effects of using the fs laser to create gliding planes inside the crystalline lens. The investigators postulated that the procedure, lentotomy, would not only help to regain elasticity and increase accommodation, but would do so without harming the lens capsule. Thickening the crystalline lens to reduce the loss of accommodation forms the basis of the procedure.

Cuts were made by scanning and focussing the fs laser beam (output power range: 2.5–10 mW; repetition rate: 5 kHz; wavelength: 780 nm; pulse duration: 125 fs) inside the lens tissue. Geometric cuts, including patterns in annular, sagittal, and cylinder shapes, were made to create the gliding planes. Results showed that creating the gliding planes increased the accommodative ability by approximately 14% for 8-plane steering-wheel patterns and 26% for 12-plane cuts with frontal or conical annular cuts. The investigators noted that flexibility increased with the number of sagittal planes; 4, 8, and 12 planes boasted an 8.2, 16.6 and 26.6% increase in accommodation. Further investigation is warranted although initial results look promising, with the procedure allowing a shorter procedure time as well as increasing the quality of the cuts.

Another proposed method of presbyopic correction is photophaco modulation [17]. Using six fresh porcine lenses and six living rabbit eyes, it could be demonstrated how this procedure safely modified the lens for presbyopia correction by induction of lens fiber disruption with the low-energy fs laser. Immediately after laser application, there was good lens clarity, with cataract formation in only one rabbit eye. There was no evidence of focal lens opacification and no increase of light scatter. The investigators concluded that fs laser photodisruption was able to safely modify the paracentral lens nucleus, epinucleus, and cortex enough to result in presbyopia correction.

Penetrating keratoplasty

Although adoption of PKP is limited among corneal surgeons, it is still a newer and exciting use of the fs laser. Manual PKP requires a long learning curve and a lengthy procedure time [18]. The fs laser can be used to create a "top hat"-shaped PKP that boasts creation of penetrating corneal incisions in one step. Additionally, Steinert et al. [18] found that certain prototype software could be used to create intrastromal laser pulses and plasma bubbles that in turn placed symmetrical radial marks in the cornea so-called alignment incisions, aiding suture placement.

It has been found that the "top hat"-PKP configuration causes less wound leakage and provides a platform for looser sutures, which theoretically may decrease suture-induced astigmatism and allow faster visual recovery [19]. Additionally, using the fs laser during PKP provides a better match at the wound edge between donor and recipient.

Cataract surgery

Using lasers to perform certain parts of cataract extraction harkens back to the days when the Nd:YAG laser for posterior capsulotomy was first introduced. These days, the interest in