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REVIEW

Advances in femtosecond laser technology

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Abstract: Femtosecond laser technology has become widely adopted by ophthalmic surgeons. The purpose of this study is to discuss applications and advantages of femtosecond lasers over traditional manual techniques, and related unique complications in cataract surgery and corneal refractive surgical procedures, including: LASIK flap creation, intracorneal ring segment implantation, presbyopic treatments, keratoplasty, astigmatic keratotomy, and intrastromal lenticule procedures.

Keywords: laser therapy, refractive surgical procedures, intracorneal ring, laser in situ keratomileusis, keratoplasty, presbyopia, cataract extraction, astigmatism surgery

Introduction

The femtosecond (FS) laser operates in the infrared range (wavelength: 1,053 nm) and uses ultrafast pulses with a duration of 100 fs (10–15 seconds). Like neodymium-doped yttrium aluminum garnet laser, FS laser is solid and capable of causing disruption in stromal tissue through the principle of photoionization, resulting in the rapid formation of a cloud of free electrons and ionized molecules. Small volumes of tissue are vaporized, with the formation of cavitation bubbles made up of carbon dioxide and water. This gas is dissipated in the tissue, forming a cleavage plane.[1]

The prototype of the first corneal surgery with FS laser was developed in US in the early 1990s.[2] In 2001, the first LS laser (Intralase Pulsion) was approved by the US Food and Drug Administration for the creation of corneal lamellae in laser-assisted in situ keratomileusis (LASIK). Improvements in the technology occurred quickly, with the increase in pulse frequency and reduction in the amount of energy released so that only the desired tissue was affected while adjacent areas remained intact, thereby ensuring fewer harmful effects – the main advantage of this method.[3,4]

FS laser currently has numerous applications and is no longer restricted to the cornea. The main uses of this method include the flap creation in LASIK surgery, tunneling of the cornea for the implantation of an intrastromal ring, and the creation of corneal incisions and lamellae in lamellar and penetrating keratoplasty. FS laser has also been used for the removal of corneal lenticules for the correction of myopia, presbyopia, natural astigmatism, and post-corneal implant astigmatism.[1] Lately, FS laser has also been used in phacoemulsification surgery for incisions, fragmentation of the nucleus and capsulorhexis.[5–15]

Commercially available FS laser types include IntraLase (Abbott Medical Optics Inc., Santa Ana, CA, USA), Femtec (20/10 Perfect Vision AG, Heidelberg, Germany) Femto LDV (Ziemer Ophthalmic Systems, Port, Switzerland), VisuMax (Carl Zeiss Meditec AG, Jena, Germany), WaveLight FS200 (Alcon Laboratories, Inc., Fort Worth, TX, USA), LenSx (Alcon Laboratories, Inc.),[16] Victus (Bausch & Lomb Incorporated,

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Table 1 Commercially available femtosecond lasers

Parameter	Femto LDV	WaveLight FS 200	FemTec 20/10	IntraLase iFS 150	Zeiss VisuMax	Victus	Catalys	LensX
Wavelength (nm)	1,045	1,045	1,053	1,053	1,043	1,040±25	1,030	1,030±5
Centration	Mechanical	Computer	Mechanical	Computer	Mechanical	Computer	Computer	Computer
Visualization of surgery	Virtual	Visual and virtual	Visual	Visual and virtual	Visual	OCT	OCT	OCT
Mobile	Yes	No	No	No	No	No	No	No
Applanation surface	Planar	Modified Planar	Curved	Planar	Curved	Curved	Curved	Curved

Abbreviation: OCT, optical coherence tomography.

Bridgewater, NJ, USA), and Catalys (Abbott Medical Optics Inc., Santa Ana, CA)[17] (Table 1).

LASIK flap creation

LASIK surgery is widely used in the correction of refractive errors and involves the creation of an anterior lamella, followed by stromal photoablation using an excimer laser.[18] The creation of this lamella is an important step in the surgical procedure and can be performed by two methods: the mechanical microkeratome and the FS laser microkeratome.[19] Aiming to improve the predictability of refractive surgery and avoid its complications, the flap creation has been richly studied.

The advantages of FS laser flap creation compared to mechanical microkeratomes include reduced incidence of flap complications, greater surgeon choice of flap diameter, thickness, side-cut angle, hinge position and length, decreased risk of infection, less induction of dry eye, less effect on corneal sensitiviity, increased precision with improved flap safety and thickness predictability, and the ability to cut thinner flaps.[20–24]

LASIK flaps created by FS laser present a significantly lower deviation from the target thickness and are more predictably than flaps created by microkeratome, making LASIK surgery safer and more accurate.[25,26] Thinner flaps make corneal surgery possible in patients with reduced thickness of the cornea and more severe ametropia and are associated with fewer changes in corneal biomechanics,[27] thereby reducing the percent of tissue altered (PTA) and the risk of postoperative ectasia.[28]

Chen et al performed a meta-analyses to compare FS laser to mechanical microkeratomes for myopic LASIK and found similar results in regards to safety and efficacy, although FL laser could offer potential advantages in predictability.[29]

LASIK flaps created by FS laser appears to be equivalent in relation to the wavefront analysis and final visual acuity. The FS laser offers advatages over microkeratomes. These include increased precision, a reduced incidence of flap complications, and the ability to cut thinner flaps. The use of the FS laser has made flap creation in laser in situ keratomileusis surgery safer and more predictable.

Intrastromal corneal ring segment (ICRS) implantation

ICRS implantation has been proposed as an additive surgical procedure for keratoconus correction to delay, if not prevent, the need for corneal grafting.[30,31] The goal of ICRS implantation is to regularize the front surface of the cornea while maintaining the existing biomechanical status of the underlying stroma.[32]

Manual corneal tunneling for the implantation of an intrastromal ring offers good outcomes, but can result in complications such as epithelial defects, perforation, and segment superficialization and extrusion.[33–35]

Comparing the two techniques, Kubaloglu et al found similar visual and refractive results, but significantly fewer complications with FS laser.[36] Rabinowitz et al and Carrasquillo et al compared FS laser and mechanical tunnelization in the treatment of ectatic eyes, but observed no differences in visual and refractive outcomes.[37,38]

Despite the overall lower incidence of complications reported for FS laser, Pinero and Alio reported cases of ring migration and extrusion in tunnels made with FS laser, showing that this technique also has drawbacks.[39]

The tunnel created by the FS laser can also be used for procedures combined with crosslinking. Studies revealed that intracorneal riboflavin injection for combined collagen crosslinking and ICRS implantation was safe and may provide more penetration without epithelial removal.[40,41]

Theoretically, compared with mechanical tunnel creation, which is based on surgeon skill, the FS laser-assisted procedure should generate a more accurate stromal dissection with less depth variability, leading to better visual and refractive results. This could lead to a more predictable refractive result. But further studies are required to confirm this theory.[37,42]

Presbyopia treatment

According to recent estimates, presbyopia is the most common type of refractive error, affecting more than two billion people worldwide.[43]

The FS laser may be used to create intrastromal pockets and provides several different therapies in ophthalmology;

for example, the MyoRing, a continuous full-ring implant which is implanted into the corneal pocket for the treatment of myopia and keratoconus. Pockets are used for corneal inlays in presbyopia.[44]

The field of refractive surgery has seen a growing interest in the use of corneal implants for the treatment of this condition. Such implants (referred to as inlays) can be inserted using a microkeratome or FS laser,[45,46] however, the latter provides greater predictability.[47]

Intrastromal FS laser treatment (INTRACOR) using FS laser is another option to correct presbyopia by selectively changing the topographic and refractive characteristics of the central portion of the cornea. This technique was first described in 2009 and makes the cornea multifocal through circular stromal incisions made around the pupil. The cut pattern induces a corneal curvature change with a central steepening with reduced spherical aberrations after surgery. Technolas (Technolas Perfect Vision Gmbh, München, Germany) is the model used for INTRACOR.[48,49]

An advantage of the use of an inlay resides in the fact that, unlike INTRACOR or PrebyLasik, it can be removed if the patient is unable to adapt to it.[50]

Presbyopia correction methods involving FS laser have not yet been extensively evaluated with regard to long-term results, however, this laser function seems to be quite promising.

Astigmatic keratotomy

The creation of incisions for the correction of astigmatism, either natural or secondary to keratoplasty, trauma, cataract surgery or other causes, constitutes an important use of FS laser.[51,52]

Excimer laser, limbal relaxing incisions, compressive sutures, and wedge excision can be used for the correction of postsurgical astigmatism.[53,54] However, astigmatic keratectomy is the most common technique. It consists of a circular corneal incision with a diameter smaller than the donor-receptor junction, which can be performed either manually or with FS laser.[55]

Using FS laser, Nubile et al found a reduction in the cylinder from 7.16±2.70 D in the preoperative period to 2.39±1.62 D 6 months after the procedure in patients who underwent corneal transplantation, in addition to a 58% reduction in absolute astigmatism observed in the topography.[56]

The manual method can lead to decentration, epithelial defects, abrasions, and perforations. In contrast, FS laser produces more precise and stable cuts and is associated with fewer complications.[57,58] However, the precision of FS laser technology in creating incisions still needs to be matched with better nomograms for an accurate correction. This technology is still evolving and advanced refinements are currently being developed in the newer generation FS laser devices.

Keratoplasty

FS laser is currently used in penetrating and lamellar keratoplasty (LK). It provides precise incisions on different planes with minimal harm to adjacent tissues.[59,60]

The use of an FS laser optimizes the LK technique by raising the precision of lamellar dissections and side cuts. This technique also has less risk of microperforations while it is possible to visualize the cornea during lamellar dissection. In theory, the smooth interface should improve visual results.[61,62]

Penetrating keratoplasty performed with a FS laser is capable of creating circular or multiplanar incisions for corneal trephinations for penetrating keratoplasty, which potentially increases graft-host interface surface area, better wound apposition, fit, and stability.[63] According to Farid et al, it improves residual refractive errors and leads to earlier visual recovery compared to the conventional technique.[8]

Deep anterior LK, which involves the removal of anterior diseased cornea while leaving deeper tissue intact, is becoming a more widely used corneal surgery. Its superiority over penetrating keratoplasty lies in the fact that the donor graft is transplanted devoid of its main antigenic load, the corneal endothelium.[64] Alio et al, in a recent study, compared the outcomes of deep anterior LK using FS laser and conventional manual technique. FS assisted and manual techniques show comparable visual and refractive outcomes at 1 year after the surgery.[65]

The FS laser represents, at this moment, an excellent choice in order to achieve several goals: good wound apposition, biomechanical stable incision, minimal suture tension, rapid recovery of the wound and vision, and a less invasive surgical procedure that offers the patient the best results in terms of refractive outcomes.[66]

Small incision lenticule extraction

Small incision lenticule extraction (SMILE) technology is a technology for correcting refractive errors that has become available for intrastromal lenticule cutting and subsequent lenticule extraction. SMILE can be performed with FS Visumax (VisuMax; Carl Zeiss Meditec AG), and seems to affect the biomechanics of the cornea less due to the absence of an extensive cut (as in LASIK surgery) and stromal photoablation. Thus, less stromal tissue is consumed.[67]

A smaller incision also means less nerve damage, with a lower incidence of symptoms of dry eye following refractive surgery.[68] According to Dong et al, corneal cell death and inflammatory reactions are less severe with SMILE than with LASIK.[69]

As SMILE can only correct myopia and low degree astigmatism, and is only performed with one FS laser model, this technique is not yet widely employed by refractive surgeons.[70,71] Moreover, studies on this method have had short follow-up periods due to the recent advent of SMILE.

FS laser-assisted cataract surgery

The preferred method of removing cataracts in the developed world is phacoemulsification. However, the advent of FS lasers has changed cataract surgery profoundly. FS laser-assisted cataract surgery (FLACS) includes creating manual corneal incisions and anterior capsulotomies, followed by phacoemulsification.[72,73]

There are actually five platforms for FS laser cataract surgery. They differ in image capturing, versatility, docking, lens fragmentation patterns, and speed of action, however they are technologically similar. The five platforms are: LenSX (Alcon LenSX, Inc., Aliso Viejo, CA, USA), LensAR (LENSAR, Inc., Winter Park, FL, USA), Catalys Precision Laser System (OptiMedica Corporation), VICTUS (Bausch & Lomb Incorporated), and the FEMTO LDV Z (Ziemer Ophthalmic Systems).[74]

One intraoperative advantage of FLACS is a reduction of energy during phacoemulsification, as described by Abell et al, which can lead to a reduced corneal endothelium cell loss (common in standard phacoemulsification).[75] Knorz reported a 25% decrease in endothelial cell loss in laser cases compared with manual cases at 1 month postoperatively.[76]

Some authors have suggested the benefits of FLACS over conventional cataract surgery include reproducibility of anterior capsulotomy and precision of corneal incision.[77,78] Friedman et al reported a significant difference between FS laser and manual capsulorhexis with regard to the size and shape of the extracted capsule, with a mean deviation from centration of 77±47 micrometers in the laser group.[79] Nagy et al observed that FS laser capsulotomies were more regularly shaped and had improved centration and better intraocular lens/capsule overlap than manual capsulorhexes.[80] These can lead to an expansion of the indications of refractive lens exchange and limbal-relaxing incisions, bringing the revolution not only to cataract surgery but also to the refractive surgery area.

Despite the good results, some complications have been reported in FLACS, such as suction breaks and capsular block syndrome. The failure in docking technique can also lead to tilting of the capsule and lens, incomplete capsulotomy, capsular tags, and secondary anterior capsule tear formation.[81,82]

FS laser uses less energy, causing less damage to the cornea than conventional surgery. The incisions in the cornea appear to be more stable and the capsulorhexis more precise than the manual technique, which favors higher optical quality, and more accurate premium intraocular lens centration. In addition, low rates of complications are described in FS technology when compared to manual phacoemulsification. However, FS technology will not eliminate the need for modern phacoemulsification, as this is necessary to emulsify hard nuclei, and there is also the issue of higher cost than conventional surgery.[83]

Glaucoma therapy

The treatment of glaucoma, a progressive disease which generates irreversible loss, can also benefit from the use of the FS laser in the future. An experimental study has shown that the FS laser can be used to perform sclerotomy for glaucoma therapy. The laser can make extremely precise incisions with a smoother inner surface with less peak power density.[84] Another paper describes methods for design and manufacturing of a micro-mechanical valve for a novel glaucoma implant. The implant is designed to drain aqueous humor from the anterior chamber of the eye into the suprachoroidal space in case of elevated intraocular pressure. In contrast to any existing glaucoma drainage device, the valve mechanism is located in the anterior chamber and, surrounded by aqueous humor, immune to fibrosis induced failure.[85]

Further studies are needed for the laser to become important in glaucoma therapy, but this seems to be a reality in the near future.

Conclusion

The FS laser offers a variety of new treatment possibilities in many fields of ophthalmic anterior segment surgery. With regard to surgical outcome and safety, the FS laser seems to have advantages over most mechanical devices. The role of FS laser in corneal surgery is already well established, however, its use in rock-hard cataracts is questionable and requires further evaluation. Currently, the most important factor limiting the dissemination of the FS laser is its high cost. As with any other technology, competition will likely bring down the cost of the equipment making the price per case less expensive. FS lasers hold great promise and their applications are continuing to evolve and expand in ophthalmology.

Disclosure

The authors have no conflicts of interest to disclose.

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