·Review·

Femtosecond laser in refractive and cataract surgeries

Han-Han Liu, Ying Hu, Hong-Ping Cui

Department of Ophthalmology, Shanghai East Hospital Affiliated to Tongji University, Shanghai 200120, China

Correspondence to: Hong-Ping Cui. Department of Ophthalmology, Shanghai East Hospital Affiliated to Tongji University, No.150, Jimo Road, Pudong District, Shanghai 200120, China. 2238067351@qq.com

Received: 2014-06-23 Accepted: 2014-09-15

Abstract

• **In the past few years, 9 unique laser platforms have been brought to the market. As femtosecond (FS) laser-assisted ophthalmic surgery potentially improves patient safety and visual outcomes, this new technology indeed provides ophthalmologists a reliable new option. But this new technology also poses a range of new clinical and financial challenges for surgeons. We provide an overview of the evolution of FS laser technology for use in refractive and cataract surgeries. This review describes the available laser platforms and mainly focuses on discussing the development of ophthalmic surgery technologies.**

• **KEYWORDS:** femtosecond; refractive surgery; cataract surgery

DOI:10.3980/j.issn.2222-3959.2015.02.36

Liu HH, Hu Y, Cui HP. Femtosecond laser in refractive and cataract surgeries. *Int J Ophthalmol* 2015;8(2):419-426

INTRODUCTION OF FEMTOSECOND LASER

The femtosecond (FS) laser is a near-infrared laser, working at a wavelength of 1053 nm. However the FS laser has ultrashort pulse duration at 10^{-15}s (quadrillionths of a second), allowing it to produce smaller shock waves and therefore create a smaller zone of collateral damage. The 1053 nm laser wavelength has a diameter of 0.001 mm, and can be focused to a <1.8 μm spot, which is accurate to within 5 μm and does not cause trauma to the superficial or adjacent tissue [1]. This allows precise cutting of tissue with virtually no heat development. Novel application of the FS laser has now made it possible to make advanced shaped corneal cuts by laser and to extend use range to other aspects in ophthalmology, decreasing the need to do a technically difficult and time-consuming manual dissection.

FEMTOSECOND LASER AND OCULAR SURGERIES

Femtosecond Laser and Refractive Surgery In the early 1980s, ultra short laser pulses were available in the laboratory. Improvements in generating and amplifying FS lasers have reduced the pulse energy needed for surgery [2,3]. The FS lasers in commercial use today evolved from a picosecond laser (developed by Intelligent Laser Systems at the University of Michigan), which was found to be more effective at performing intrastromal ablations. There are currently five Food and Drug Administration (FDA) approved FS laser platforms [IntraLase FS (Abbott Medical Optics Inc., CA, USA), FemTec 2010 (Technolas Perfect Vision, MO, USA), Femto LDV (Ziemer Ophthalmic Systems AG, Port, Switzerland), Visumax (Carl Zeiss Meditec AG, Jena, Germany), and Wavelight FS200 (Alcon, Fortworth, TX, USA)] for use in corneal refractive surgery. Of these, the IntraLase FS laser was the first commercially available FS laser and is currently the most widely used platform [4].

Femtosecond laser for myopia and hyperopia correction When the FS laser was first developed, it did not gain tremendous notoriety until researchers determined that it could be used to cut corneal flaps as part of laser *in situ* keratomileusis (LASIK) as well as cutting tunnels for the implantation of intracorneal ring segments (ICRS) for the treatment of keratoconus. The FS-assisted flap creation is a crucial step in LASIK surgery, with advantages compared to microkeratome-related flap (Table 1)[5-10]. Although modern microkeratome-related flap complications are very uncommon, the introduction of the FS laser has improved the safety and precision of flap creation [11].

Moreover, Carl Zeiss Meditec introduced a new approach called FS Lenticule Extraction (FLEx) for refractive surgery to correct myopia and myopic astigmatism. This new innovation uses a FS laser alone, compared with other procedures that require both excimer and FS laser. FLEx involves making two cuts (posterior and anterior) in the cornea that intersect in the periphery, creating a lenticule, which is ultimately removed. This cut is extended centripetally as a flap and is followed by a 270-degree side cut to form the traditional flap opening. In 2008, Sekundo *et al* [12] compared the results of FLEx and conventional LASIK with 6-month of follow-up, and concluded that there was no remarkable difference between the two groups,

Table 1 Comparison of mechanical microkeratomes and FS lasers for LASIK flap creation

Parameters	FS laser	Mechanical microkeratome
Flap	Thinner	Thicker
Corneal architecture	Less influence	Influence
IOP with suction ring	Less increase	Increase
Flap adherence	Stronger	Weaker
Thickness predictability	Improved	Worse
Induced higher order aberrations	Fewer	More
Surgically induced astigmatism	Less	More
Contrast sensitivity	Better	Worse
Dry eye	Less	More

suggesting FLEx to be a promising new corneal refractive procedure to correct myopia. Shah *et al* [13] used the FLEx procedure to create a intrastromal refractive lenticule through a 3.0 to 5.0 mm incision, and found that all-in-one FS refractive correction was safe, predictable, and effective in treating myopia and myopic astigmatism. However with the FS surgery development, there is 2 mm incision at minimum and without flap cutting in refractive surgery called small incision lenticule extraction (SMILE) was developed and gained more and more popular. Sekundo *et al* [14] reported that 88% of eyes with plano target had an uncorrected distance visual acuity (UDVA) of 20/20 or better and the mean spherical equivalent (SE) was -0.19±0.19 diopters (D) after 1y surgery. In their study there was no visually threatening complications observed. There is another study which has confirmed the efficacy, safety, and predictability of SMILE was good over a 12-month follow-up[15]. However there is argument about the decentration during SMILE surgery. Now the disputation has been settled down with the demonstration by Li *et al* [16] in their study. They have suggested that, although mild decentration occurred in the early learning curve, good visual outcomes were achieved after the SMILE surgery.

Recently Pradhan *et al* [17] have described that endokeratophakia in which a SMILE lenticule from a myopic patient is implanted into a recipient eye through a small incision to correct hyperopia. In their study we could find that endokeratophakia appears to be a viable procedure for correcting hyperopia on the cornea by implantation of an extracted myopic SMILE lenticule from a donor patient. However, posterior surface changes and epithelial remodeling resulted in only 50% of the intended correction. No adverse side effects were observed following implantation of donor tissue for 1y[17].

Femtosecond laser for presbyopia correction One of the most recent developments in the ophthalmologic application of the FS laser is its use in the correction of presbyopia. The previous correction methods for presbyopia included lens implants or monovision surgery. The intrastromal correction of presbyopia (IntraCOR procedure) has been pioneered by Ruiz *et al* [18] using the Technolas 520 FS laser platform. They studied 83 eyes of 45 patients aged 44-67y, and found that 6-12mo after the Intracor procedure, the uncorrected near visual acuity (UNVA) improved to Jaeger (J) 1 with continued improvement in mean UDVA at 6-month postoperatively and 74 (89.2%) eyes achieved both J2 and 20/25 or better at last follow-up. Another application of FS laser in the treatment of presbyopia is to reduce the hardness of the lens. In 2008, Ripken *et al* [19] used the FS laser to create gliding planes inside the crystalline lens and showed that this 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. Ackermann *et al*[20] further confirmed that FS laser treatment seemed to be no trigger for cataract formation with the study of ten Göttingen minipigs. The results showed that no laser-induced cataractogenesis was observed during the 1-year follow-up by means of slit-lamp examination of the anterior segment and Scheimpflug imaging of the lens. Tomita *et al* [21] have evaluated the visual outcomes after implantation of a Kamra small-aperture corneal inlay into a FS-created corneal pocket to treat presbyopia in patients who had previous LASIK. The mean UDVA in the operated eye decreased 1 line from 20/16 preoperatively to 20/20 6mo postoperatively and the mean UNVA improved 4 lines from J8 to J2 (P<0.001). It seems that implantation of a small-aperture inlay in post-LASIK presbyopic patients improves near vision with a minimal effect on distance vision, resulting in high patient satisfaction and less dependence on reading glasses[21]. Recently Baily *et al* [22] have reported the results of the Icolens corneal inlay 12mo after implantation in the nondominant eye of emmetropic patients through a FS laser-created corneal pocket. In their study, the mean UNVA in the surgical eye improved from N18/N24 preoperatively to N8 postoperatively; all patients had a UNVA of N16 or better and 9 (17%), of N5 or better; the UDVA in the surgical eye increased from 0.05 logMAR ±0.12 preoperatively to 0.22±0.15 postoperatively. They suggested that the new refractive-addition corneal inlay effectively corrected presbyopia in emmetropic presbyopic patients[22].

Femtosecond laser for keratoconus FS laser technology can also be used to create channels for the implantation of Intacs (Addition Technology) in patients with keratoconus. Rabinowitz *et al* [23] compared the results of Intacs insertion by creating channels using the mechanical spreader in 10 eyes with another 20 eyes using the FS lasers. The FS laser group performed better average keratometry, SE refraction, best spectacle corrected visual acuity (BSCVA) and surface asymmetry index. The biggest improvement in the FS laser group versus the mechanical group was BSCVA (P=0.09). Overall success, defined as contact lens or spectacles tolerance, was 85% in the FS laser group and 70% in the mechanical group.

Femtosecond Laser and Keratoplasty In 2005, the FDA approved the FS laser for therapeutic keratoplasty in making full thickness and partial-thickness cuts [24]. IntraLase tested the use of FS lasers for a wide range of corneal procedures in 2006, including penetrating keratoplasty (PKP), deep anterior lamellar keratoplasty (DALK) and Descemet's stripping endothelial keratoplasty (DSEK)[25-27].

Femtosecond laser and penetrating keratoplasty Manual PKP requires a long learning curve and a lengthy procedure time [28]. The application of FS laser can create complex-pattern trephination cuts for enhanced wound integrity of the graft-host junction, which theoretically may decrease suture-induced astigmatism and allow faster visual recovery[29]. The latter includes the "'top-hat" (with a larger diameter cut posteriorly), the "mushroom" (with a larger diameter cut anteriorly), the tongue-groove, the zig-zag, and the "Christmas tree" patterns. The choice of shapes and diameters in FS laser-assisted PKP or FS laser-assisted keratoplasty or IntraLase-enabled keratoplasty is dependent on individualized clinical requirement. The mushroom may be advantageous in keratoconus by providing a larger anterior refractive surface, while the top-hat may be advantageous in endothelial diseases by replacing more endothelial cells. Steinert *et al* [28] found that wound leakage occurred at 38±11 mm Hg in the traditional PKP eyes and at 240±69 mm Hg in the laser-shaped PKP groups; FS laser-assisted PKP induced astigmatism was 3.76 ±0.82 D and 3.46±1.36 D in the traditional and shaped PKP groups, respectively. The results suggested that shaped PKP using the FS laser was feasible and provided superior incision integrity compared to traditional PKP.

Femtosecond laser and anterior lamellar keratoplasty ALK is a partial thickness corneal transplantation suitable for patients with corneal dystrophies or scars resulting from trauma or infections. The FS-assisted sutureless ALK (FSSALK) can be used to treat anterior corneal pathologies with less irregular astigmatism and faster visual rehabilitation. Anterior segment optical coherence tomography (OCT) was also used to estimate corneal scarring depth in the recipient cornea. Yoo *et al* [30] used twelve consecutive eyes from 12 patients with anterior corneal scarring to measure parameters included FS laser settings, technique, UDVA, BSCVA and complications. The results suggest that FSSALK could improve UDVA and BSCVA in patients with anterior corneal pathology. Shousha *et al* [31] evaluated the long-term results of FSSALK for anterior corneal pathologies through thirteen consecutive patients who underwent this surgery and indicated that that FSSALK improved the BSCVA of patients with rapid visual rehabilitation (an average of only 8mo after surgery) and no significant induced astigmatism. Bonfadini *et al* [32] reported a variation of the FSSALK technique using a FS laser incision for surgical management of anterior corneal disease. No intraoperative adverse events were observed except one patient with developed epithelial ingrowth. Future studies with larger sample sizes are warranted to assess the risk of epithelial ingrowth with this sutureless technique. Risk factors that should be assessed include blood vessels in the interface and graft-host size disparity. Lu *et al* [33] have indicated that FS laser-assisted DALK could improve UCVA and BSCVA in patients with anterior corneal pathology and this approach shows promise as a safe and effective surgical choice in the treatment of keratoconus and post-LASIK keratectasia.

Femtosecond laser and Descemet´s membrane endothelial keratoplasty Descemet's membrane endothelial keratoplasty (DMEK) is a corneal surgical technique which selectively replaces the damaged posterior part of the cornea with a healthy donor graft retaining the rest of the tissue intact. The 60 kHz FS laser allows closer spot and line separation with lower energy levels and results in smooth stromal interface also in deeper cuts which states that higher frequency with lower energy and closer spot and line separation can create smoother stromal bed surfaces [24,25]. Increased laser speed of 150 kHz over 60 kHz allows the surgeon to perform the procedure in a shorter period of time with a tighter spot and line separation[34]. Therefore, FS lasers with higher engine speed and closer spot and line separation units can be a good rescue for preparing the donor grafts for DMEK[35-37].

Femtosecond laser and Descemet´s stripping automated endothelial keratoplasty Descemet's stripping automated endothelial keratoplasty (DSAEK) is the gold standard for the surgical treatment of corneal endothelial diseases. However, DSAEK poses major technical challenges to corneal surgeons and novel improvements are under the scope of researchers, such as the use of cultivated human corneal endothelial cells and the development of specific inserter devices to insert the endothelial graft. The idea of using a FS laser to prepare a posterior lamellar disc for endothelial keratoplasty occurred to researchers several years ago. After an in vitro study showed that it was possible, Cheng *et al* [38] first evaluated the preliminary visual results of FS-assisted DSAEK (FSDSAEK) on 20 patients with Fuchs endothelial dystrophy or aphakic/pseudophakic bullous keratopathy. Mean (SD) endothelial cell density at 6-month follow-up was 1368 (425) cells/mm^2. A 6-month follow-up showed FSDSAEK was effective in treating endothelial failure with minimal induced refractive astigmatism, limited improvement of BSCVA, and induction of a hyperopic shift. Endothelial cell count and dislocation rate were significant, which may be related to the surgical technique. So there is long way to go for the FSDSAEK [39]. But recently study showed the superiority of a microkeratome-assisted preparation of the stromal-endothelial lamella before DSAEK surgery (BSCVA of 0.33±0.11) compared with the curved interface FS laser-assisted processing (BSCVA of 0.48±0.20)[39]. Dias and Ziebarth[40] in their study showed the elasticity of the posterior stroma is 39.3% of the anterior stroma and there appears to be an elasticity gradient within the corneal stroma, which should be considered in the design and development of corneal diagnostic and treatment methods to enhance efficacy. He has further verified the anterior stroma was stiffer than the posterior stroma in human cadaver eyes [41]. That's why the quality of LASIK interface is better than the quality of DALK and DSAEK interface when cut with FS laser.

Femtosecond Laser and Cataract Surgery In 2009, Nagy *et al* [42] first reported the clinical application of the FS lasers for cataract surgery. In September 2009, the FDA proved the LenSx (ALCON, California, USA) laser for the creation of anterior capsulotomies prior to cataract surgery. In rapid succession, the application in the creation of corneal incisions and applying the fragmentation of cataracts has also been approved. In 2010, the FDA cleared FS laser systems for cataract surgery. The FS lasers equipments in the cataract surgery are not exactly the same as those used in the refractive surgeries, with respect to the improvement in the safety and the precision of the surgery. The currently available machines for cataract surgery are LenSx, LenSar (LENSAR, Inc., FL, USA), Optimedica (Abbott Medical Optics Inc., CA, USA) and Technolas FEMTEC (Technolas Perfect Vision, MO, USA)[43]. The LenSar uses Scheimpflug imaging while the LenSx technology uses a FS laser with an OCT diagnostic unit, so they have the capacity for real-time analysis of the anterior segment. There are no comparative studies that can determine which of these technologies is better than the others, although all three are different in terms of ergonomics, size and probably cost.

FS laser can be used to perform four groups of incisions: capsulotomy, lens fragmentation, astigmatic relaxing incisions, and clear corneal incisions (CCIs, including the cataract incision and paracenteses) .

Clear corneal incisions The ability of FS laser to create incisions at a precise depth and with a desired shape opens the road to cataract incisions and limbal relaxing incisions (LRIs), with a more efficient sealing than conventional clear cornea incisions [44]. The self-sealing CCIs is the preferred method to access into the anterior chamber for the superior visual outcomes and faster recovery it offers, however it has drawbacks such as the higher incidence of endophthalmitis, gaps at the internal aspect of the corneal wound, Descemet's membrane detachment and increased thickness at the incision site[44-46]. Laser-made wounds may show less features of damage and faster healing, either by virtue of the wound properties or from reductions in the mechanical stresses during the operation [44,47]. Furthermore, the FS lasers can be programmed to reproduce the ideal wound structure which will reduce the incidence of wound problems. The FS laser can make the best square wound architecture which is far more stable and stronger than rectangular wounds.

Capsulotomy Use of the FS laser has the potential to revolutionize cataract surgery with the creation of a capsulotomy, or laser-incised capsulorhexis. The capsulotomy construction is extremely important for estimating effective lens position. With the growth of premium intraocular lenses, precisely centered and measured capsulorhexis are essential to achieve optimal visual outcomes with the presbyopic correcting intraocular lens (IOLs) and toric IOLs. Consistent size and shape rhexis will allow these lenses (especially accommodating IOLs) to sit in the correct and consistent location within the capsular bag. Surgeons can easily program a specific diameter and shape into the FS laser, and create reproducible rhexis that may be paramount to achieving the best quality of vision with these premium intraocular lenses. Nagy *et al* [42] tested the precision of the attempted capsulotomy created using the FS laser, against the achieved continuous circular capsulorhexis (CCC) done by an experienced surgeon in porcine eyes. Similar results was also obtained by Yeilding *et al* [34] with the capsules obtained from clinical surgeries. The resistance of the capsular edge was also studied, the circumference stretching ratio was 2.13±0.03 mm (n=10) for the laser cases and 1.98±0.08 mm (n=8) for the CCC cases. These findings were further proved by Friedman *et al* [48] recently used porcine and cadaver eyes. Recently Szigeti *et al* [49] showed 5.5 mm capsulotomy created with a FS laser was associated with less IOL vertical and horizontal tilt compared with a 6.0 mm capsulotomy when implanting a single-optic accommodating IOL after 1-year follow-up. All these studies have shown that capsulotomies produced by the FS laser were more accurate, reproducible, and stronger than those created with the conventional manual technique.

FS laser-assisted cataract surgery can also be used in traumatic cataracts. Nagy *et al* [50] reported their cases about

Table 2 Disadvantage of FS laser-assisted cataract surgery over other cataract surgeries

Parameters	FS laser-assisted cataract surgery	Other cataract surgeries
Price	Expensive	Cheap
IOP	Increase IOP[1]	Normal IOP
Posterior hyaloid detachment	Few	Seldom
Transient choroidal Circulation abnormalities	Few	Scarcely
Macular hemorrhage	Tiny	Seldom
Optic atrophy	Tiny	Scarecely
Storage space	Larger	Large

[1]Peak increase in IOP is 18.5 mm Hg[62] and 12.0 mm Hg[63] using the Catalys Precision Laser System with Liquid Optics Interface.

this. The first case developed acute traumatic cataract due to penetrating injury of the cornea and the anterior lens capsule; the second developed traumatic cataract 11y after a penetrating corneal injury; and the third developed a "white" cataract 12mo after blunt ocular trauma. In all cases, 4.5-mm capsulorrhexis and corneal incisions were performed using a LenSx FS laser system, and nucleus liquefaction with the laser was performed additionally in the second case. Results indicate that a FS laser can be used successfully in certain instances of traumatic cataract after penetrating eye injury, even if an anterior capsule laceration is present, and also after blunt trauma resulting in "white" cataracts.

For capsulotomy shape, each company used different measurement techniques, so a comparison is not easily assessed. OptiMedica measured circularity as a function of capsulotomy diameter and area with 1 being perfectly circular. OptiMedica laser capsulotomies measured 0.94 ±0.04 [51]. LenSar used a residuals analysis technique that showed a six-fold increase in circularity for laser over manual (3±5 mm for laser *vs* 20 ±13 mm for manual) [52]. LenSx laser capsulotomies were "significantly rounder" [52] than manual continuous curvilinear capsulorhexis.

Lens fragmentation The amount of energy used for phacoemulsification correlates to endothelial cell loss as well as postoperative inflammation. FS lasers have the ability to pretreat, segment or soften the lens to minimize the energy and trauma required for phacoemulsification and removal, and help to speed recovery and achieve better visual outcomes. Moreover, the laser procedure is performed before any surgical entry; the open-eye time is reduced with increased safety as well as surgical efficacy. In a series of 60 eyes treated with the FS laser and 45 with conventional phacoemulsification as control, Edwards *et al* [53] showed that BSCVA (0.05±0.10) at 3mo in the laser group was better than in the control group (0.03±0.05).

Softening of the nucleus with the FS laser will reduce the need for ultrasound power and ultimately make the procedure safer, with less risk for complications, such as posterior capsular tears. Fishkind *et al* [54] showed a marked reduction in ultrasound energy for cataracts of all lens opacities classification system grades. The percentage reduction varied by company and grade of cataract, but was 33% at least. In terms of the reduction of the phaco energy required during the procedure, Frey *et al* [55] reported that for LOCSIII Grade 1 cataract, mean cumulative dispersive energy was reduced by 26.4%, whereas for Grade 2 the reduction was 59.1%. A statistically significant reduction of effective phacoemulsification time of lens fragmentation was also noted in Conrad-Hengerer's study. They have demonstrated the effective phacoemulsification time in FS laser-assisted phacoemulsification group and the standard procedure group was 0.16±0.21s, 4.07±3.14s respectively[56].

Advantages and disadvantages Apart from the incomparable advantage of FS laser mentioned above in the field of cataract surgery, recently Nagy *et al* [57] evaluated and compared thickness changes in the retinal layers in the macula with OCT segmentation software after FS laser-assisted phacoemulsification (study group) and conventional phacoemulsification (control group). It was encouraging that after cataract surgery, macular edema was detectable mainly in the outer nuclear layer in both groups but was significantly less using the FS laser platform in their results. Takács *et al* [58] have demonstrated that FS laser-assisted cataract surgery causes less corneal edma in the early postoperative period and may cause less trauma to corneal endothelial cells than manual phacoemulsification.

In the Roberts *et al* [59] experience, the surgical outcomes and safety of laser cataract surgery improved significantly with greater surgeon experience, development of modified techniques, and improved technology.

However, despite the recent enthusiasm and hope for what the future entails, there are still several challenges for the use of FS laser in cataract surgery that must be faced (Table 2)[60,61]. The FS laser-assisted cataract surgery still has a long way to go.

Correction of Astigmatism

Astigmatic relaxing incisions Today, the goal of cataract surgery is to achieve near emmetropia. Refractive cataract surgery has become a reality for the modern phacosurgeon, and control of astigmatism plays a vital role in this quest for optical refractive outcomes. Just as for LASIK, FS laser technology can deliver the necessary accuracy and precision to improve beyond current clinical outcomes.

A number of effective options exist to minimize postoperative astigmatism, such as placing the cataract incision on the steep corneal meridians; use of adjunctive corneal or LRIs; or even using advanced technology. However, the manual incision is technically demanding. Inconsistencies in the results of manual LRIs are presumed to be related to imprecision in depth, axis, arc length, and optic zone. An axis misalignment of just 58 results in a 17% reduction in effect [64]. Conceivably, the improved accuracy and reproducibility afforded by the FS lasers could improve the reliability of outcomes of laser LRIs compared with manual LRIs. Nichamin *et al* [64] showed that the cataract laser systems can perform corneal or LRIs to correct up to 3.5 diopters of astigmatism, flatten the steepest meridian of the cornea, eliminate a source of refractive error.

Intrastromal arcuate keratotomy FS laser could produce the effective creation of precise, purely intrastromal, arcuate incision patterns with an excellent safety profile, rapid recovery, and stability of vision without the known risks associated with incisions that penetrated Bowman membrane. Rückl *et al* [65] have treated patients with corneal astigmatism (naturally occurring or after cataract surgery) with an FS laser by performing paired arcuate cuts on the steep axis completely placed within the corneal stroma. After a 6-month follow-up, the mean refractive cylinder was reduced significantly from 1.41±0.66 D to 0.33±0.42 D and topographic astigmatism was reduced significantly from 1.50±0.47 D preoperatively to 0.63±0.34 D.

Femtosecond laser and post-keratoplasty astigmatism FS laser can be utilized in astigmatic keratotomy incisional surgery in both corneal grafts and native corneas to correct high degrees of post-keratoplasty astigmatism. Specific incisional width, depth and length can be programmed into the laser, allowing the incisions to be more precise. The technique also carries less risk of corneal perforation, as compared to a free-hand diamond blade technique. Nubile *et al*[66] concluded that accurate keratotomies performed with the FS laser were effective in reducing post-keratoplasty astigmatism. Laser-generated incisions within the graft button presented precise geometry and reliable depth of incision, with a wound healing pattern characterized by mild fibrosis. In addition, Kumar *et al* [67] also demonstrated that IntraLase-enabled astigmatic keratotomy was an effective treatment for high astigmatism (>5 D) after penetrating keratoplasty in a study of 34 patients. With the use of the FS laser creating astigmatic keratotomies (FS-AK) in the scope of a retrospective case series, Kook *et al* [68] have evaluated a novel technique for the correction of postoperative astigmatism after penetrating keratoplasty. In their results, the postoperative mean UDVA was 1.12, 0.47 of BSCVA, mean subjective cylinder -4.1 D, and mean topometric astigmatism 6.5 D comparing with the preoperative mean UDVA was 1.27, 0.55 of BSCVA, mean subjective cylinder -7.4 D, and mean topometric astigmatism 9.3 D. FS-AK seems to be a safe and effective tool for the correction of higher corneal astigmatisms. However, due to the biomechanical properties of the cornea and missing empirical data for the novel FS-AK technology, higher numbers of patients are necessary to develop optimal treatment nomograms to improve the visual outcomes [68]. Future studies may help refine the treatment parameters required to achieve reduction of cylinder with greater accuracy.

CONCLUSION

Advancements in technology have allowed measurable improvements in the surgical safety, efficacy, speed, and versatility of FS lasers in ophthalmology. The FS laser has been used in refractive surgeries and keratoplasty, and the perspectives for the application of FS laser can be considered the future for cataract surgeries or non-invasive glaucoma drainage surgeries. It is likely that successful implementation into ophthalmic use will continue to flourish.

ACKNOWLEDGEMENTS

Conflicts of Interest: Liu HH, None; **Hu Y,** None; **Cui HP,** None.

REFERENCES

1 Lubatschowski H, Maatz G, Heisterkamp A, Hetzel U, Drommer W, Welling H, Ertmer W. Application of ultrashort laser pulses for intrastromal refractive surgery. *Graefes Arch Clin Exp Ophthalmol* 2000;238(1):33-39

2 Fork RL, Greene BI, Shank CV. Generation of optical pulses shorter than 0.1 psec by colliding pulse mode locking. *Appl Phys Lett* 1981;38:671

3 Fork RL, Shank CV, Yen RT. Amplification of 70-fs optical pulses to gigawatt powers. *Appl Phys Lett* 1982;41:223

4 Slade SG. The use of the femtosecond laser in the customisation of corneal flaps in laser in situ keratomileusis. *Curr Opin Ophthalmol* 2007;18(4):314-317

5 Talamo JH, Meltzer J, Gardner J. Reproducibility of flap thickness with IntraLase FS and Moria LSK-1 and M2 microkeratomes. *J Refract Surg* 2006;22(6):556-561

6 Friedlaender MH. LASIK surgery using the IntraLase femtosecond laser. *Int Ophthalmol Clin* 2006;46(3):145-153

7 Slade SG. Thin-flap laser assisted in situ keratomileusis. *Curr Opin Ophthalmol* 2008;19(4):325-329

8 Salomão MQ, Ambrósio R Jr, Wilson SE. Dry eye associated with laser in situ keratomileusis: mechanical microkeratome versus femtosecond laser. *J Cataract Refract Surg* 2009;35(10):1756-1760

9 Moshirfar M, Hatch BB, Chang JC, Kurz CJ, Eugarrios MF, Mifflin MD. Prospective, contralateral comparison of 120-μm and 90-μm LASIK flaps using the IntraLase FS60 femtosecond laser. *J Refract Surg* 2011;27(4):251-259

10 Zhou Y, Tian L, Wang N, Dougherty PJ. Anterior segment optical

coherence tomography measurement of LASIK flaps: femtosecond laser vs microkeratome. *J Refract Surg* 2011;27(6):408-416

11 Salomão MQ, Wilson SE. Femtosecond laser in laser *in situ* keratomileusis. *J Cataract Refract Surg* 2010;36(6):1024-1032

12 Sekundo W, Kunert K, Russmann C, Gille A, Bissmann W, Stobrawa G, Sticker M, Bischoff M, Blum M. First efficacy and safety study of femtosecond lenticule extraction for the correction of myopia: six-month results. *J Cataract Refract Surg* 2008;34(9):1513-1520

13 Shah R, Shah S, Sengupta S. Results of small incision lenticule extraction: all-in-one femtosecond laser refractive surgery. *J Cataract Refract Surg* 2011;37(1):127-137

14 Sekundo W, Gertnere J, Bertelmann T, Solomatin I. One-year refractive results, contrast sensitivity, high-order aberrations and complications after myopic small-incision lenticule extraction (ReLEx SMILE). *Graefes Arch Clin Exp Ophthalmol* 2014;252(5):837-843

15 Ang M, Mehta JS, Chan C, Htoon HM, Koh JC, Tan DT. Refractive lenticule extraction: Transition and comparison of 3 surgical techniques. *J Cataract Refract Surg* 2014;40(9):1415-1424

16 Li M, Zhao J, Miao H, Shen Y, Sun L, Tian M, Wadium E, Zhou X. Mild decentration measured by a Scheimpflug camera and its impact on visual quality following SMILE in the early learning curve. *Invest Ophthalmol Vis Sci* 2014;55(6):3886-3892

17 Pradhan KR, Reinstein DZ, Carp GI, Archer TJ, Gobbe M, Gurung R. Femtosecond laser-assisted keyhole endokeratophakia: correction of hyperopia by implantation of an allogeneic lenticule obtained by SMILE from a myopic donor. *J Refract Surg* 2013;29(11):777-782

18 Ruiz LA, Cepeda LM, Fuentes VC. Intrastromal correction of presbyopia using a femtosecond laser system. *J Refract Surg* 2009;25(10):847-854

19 Ripken T, Oberheide U, Fromm M, Schumacher S, Gerten G, Lubatschowski H. fs-Laser induced elasticity changes to improve presbyopic lens accommodation. *Graefes Arch Clin Exp Ophthalmol* 2008; 246(6):897-906

20 Ackermann R, Kunert KS, Kammel R, Bischoff S, Bühren SC, Schubert H, Blum M, Nolte S. Femtosecond laser treatment of the crystalline lens: a 1-year study of possible cataractogenesis in minipigs. *Graefes Arch Clin Exp Ophthalmol* 2011;249(10):1567-1573

21 Tomita M, Kanamori T, Waring GO 4th, Nakamura T, Yukawa S. Small-aperture corneal inlay implantation to treat presbyopia after laser in situ keratomileusis. *J Cataract Refract Surg* 2013;39(6):898-905

22 Baily C, Kohnen T, O'Keefe M. Preloaded refractive-addition corneal inlay to compensate for presbyopia implanted using a femtosecond laser: one-year visual outcomes and safety. *J Cataract Refract Surg* 2014;40(8): 1341-1348

23 Rabinowitz YS, Li X, Ignacio TS, Maguen E. INTACS inserts using the femtosecond laser compared to the mechanical spreader in the treatment of keratoconus. *J Refract Surg* 2006;22(8):764-771

24 Buratto L, Böhm E. The use of the femtosecond laser in penetrating keratoplasty. *Am J Ophthalmol* 2007;143(5):737-742

25 Hoffart L, Proust H, Matonti F, Conrath J, Ridings B. Correction of postkeratoplasty astigmatism by femtosecond laser compared with mechanized astigmatic keratotomy. *Am J Ophthalmol* 2009;147 (5): 779-787

26 Buzzonetti L, Petrocelli G, Laborante A, Mazzilli E, Gaspari M, Valente P. Arcuate keratotomy for high postoperative keratoplasty astigmatism performed with the intralase femtosecond laser. *J Refract Surg* 2009;25(8): 709-714

27 Levinger E, Bahar I, Rootman DS. IntraLase-enabled astigmatic keratotomy for correction of astigmatism after Descemet stripping automated endothelial keratoplasty: a case report. *Cornea* 2009;28 (9): 1074-1076

28 Steinert RF, Ignacio TS, Sarayba MA. "Top hat"-shaped penetrating keratoplasty using the femtosecond laser. *Am J Ophthalmol* 2007;143(4): 689-691

29 Busin M. A new lamellar wound configuration for penetrating keratoplasty surgery. *Arch Ophthalmol* 2003;121(2):260-265

30 Yoo SH, Kymionis GD, Koreishi A, Ide T, Goldman D, Karp CL, O'Brien TP, Culbertson WW, Alfonso EC. Femtosecond laser-assisted sutureless anterior lamellar keratoplasty. *Ophthalmology* 2008;115 (8): 1303-1307

31 Shousha MA, Yoo SH, Kymionis GD, Ide T, Feuer W, Karp CL, O'Brien TP, Culbertson WW, Alfonso E. Long-term results of femtosecond laser-assisted sutureless anterior lamellar keratoplasty. *Ophthalmology* 2011;118(2):315-323

32 Bonfadini G, Moreira H, Jun AS, Campos M, Kim EC, Arana E, Zapparoli M, Ribas Filho JM, McDonnell PJ. Modified femtosecond laser-assisted sutureless anterior lamellar keratoplasty. *Cornea* 2013;32 (4):533-537

33 Lu Y, Shi YH, Yang LP, Ge YR, Chen XF, Wu Y, Huang ZP. Femtosecond laser-assisted deep anterior lamellar keratoplasty for keratoconus and keratectasia. *Int J Ophthalmol* 2014;7(4):638-643

34 Yeilding RH, Villar-Kuri J, Naranjo-Tackman R. Evaluation of size and shape of anterior lens capsules after photodisruption laser capsulotomy and continuous curvilinear capsulorrhexis. *Invest Ophthalmol Vis Sci* 2009;50: E-Abstract1145

35 Sarayba MA, Ignacio TS, Binder PS, Tran DB. Comparative study of stromal bed quality by using mechanical, IntraLase femtosecond laser 15- and 30-kHz microkeratomes. *Cornea* 2007;26(4):446-451

36 Sarayba MA, Ignacio TS, Tran DB, Binder PS. A 60 kHz IntraLase femtosecond laser creates a smoother LASIK stromal bed surface compared to a Zyoptix XP mechanical microkeratome in human donor eyes. *J Refract Surg* 2007;23(4):331-337

37 Parekh M, Salvalaio G, Ruzza A, Camposampiero D, Griffoni C, Zampini A, Ponzin D, Ferrari S. Posterior lamellar graft preparation: a prospective review from an eye bank on current and future aspects. *J Ophthalmol* 2013; 2013:769860

38 Cheng YY, Hendrikse F, Pels E, Wijdh RJ, van Cleynenbreugel H, Eggink CA, van Rij G, Rijneveld WJ, Nuijts RM. Preliminary results of femtosecond laser-assisted descemet stripping endothelial keratoplasty. *Arch Ophthalmol* 2008;126(10):1351-1356

39 Vetter JM, Butsch C, Faust M, Schmidtmann I, Hoffmann EM, Sekundo W, Pfeiffer N. Irregularity of the posterior corneal surface after curved interface femtosecond laser-assisted versus microkeratome-assisted descemet stripping automated endothelial keratoplasty. *Cornea* 2013;32(2): 118-124

40 Dias JM, Ziebarth NM. Anterior and posterior corneal stroma elasticity assessed using nanoindentation. *Exp Eye Res* 2013;115:41-46

41 Dias J, Diakonis VF, Kankariya VP, Yoo SH, Ziebarth NM. Anterior and posterior corneal stroma elasticity after corneal collagen crosslinking treatment. *Exp Eye Res* 2013;116:58-62

42 Nagy Z, Takacs A, Filkorn T, Sarayba M. Initial clinical evaluation of an intraocular femtosecond laser in cataract surgery. *J Refract Surg* 2009;25 (12):1053-1060

43 Donaldson KE, Braga-Mele R, Cabot F, Davidson R, Dhaliwal DK, Hamilton R, Jackson M, Patterson L, Stonecipher K, Yoo SH; ASCRS Refractive Cataract Surgery Subcommittee. Femtosecond laser-assisted cataract surgery. *J Cataract Refract Surg* 2013;39(11):1753-1763

44 Masket S, Sarayba M, Ignacio T, Fram N. Femtosecond laser-assisted cataract incisions: architectural stability and reproducibility. *J Cataract Refract Surg* 2010;36(6):1048-1049

45 Fine IH. Clear corneal incisions. *Int Ophthalmol Clin* 1994; 34 (2): 59-72

46 Xia Y, Liu X, Luo L, Zeng Y, Cai X, Zeng M, Liu Y. Early changes in clear cornea incision after phacoemulsification: an anterior segment optical coherence tomography study. *Acta Ophthalmol* 2009;87(7):764-768

47 Stonecipher K, Ignacio TS, Stonecipher M. Advances in refractive surgery: microkeratome and femtosecond laser flap creation in relation to safety, efficacy, predictability, and biomechanical stability. *Curr Opin Ophthalmol* 2006;17(4):368-372

48 Friedman NJ, Palanker DV, Schuele G, Andersen D, Marcellino G, Seibel BS, Batlle J, Feliz R, Talamo JH, Blumenkranz MS, Culbertson WW. Femtosecond laser capsulotomy. *J Cataract Refract Surg* 2011;37 (7): 1189-1198

49 Szigeti A, Kránitz K, Takacs AI, Miháltz K, Knorz MC, Nagy ZZ. Comparison of long-term visual outcome and IOL position with a single-optic accommodating IOL After 5.5- or 6.0-mm Femtosecond laser capsulotomy. *J Refract Surg* 2012;28(9):609-613

50 Nagy ZZ, Kr á nitz K, Takacs A, Filkorn T, Gergely R, Knorz MC. Intraocular femtosecond laser use in traumatic cataracts following penetrating and blunt trauma. *J Refract Surg* 2012;28(2):151-153

51 Batlle J. Prospective study of size and shape accuracy of OptiMedica Femtosecond Laser Capsulotomy *vs* manual capsulorohexis [abstract]. In: Program and Abstracts of XXVIII Congress of the ESCRS; 4-8 September 2010; Paris, France

52 Nichamin LD, Naranjo Tackman R, VillarKuri J, Fishkind W. Laser capsulotomy with the LensAR laser system [abstract]. In: Program and Abstracts of XXVIII Congress of the ESCRS; 4-8 September 2010; Paris, France

53 Edwards KH, Frey RW, Naranjo-Tackman R. Clinical outcomes following laser cataract surgery. *Invest Ophthalmol Vis Sci* 2010;51: E-Abstract

54 Fishkind W, Uy H, Tackman RN, Kuri JV. Alternative fragmentation patterns in femtosecond laser cataract surgery [abstract]. In: Program and Abstracts of American Society of Cataract and Refractive Surgeons Symposium on Cataract, IOL and Refractive Surgery; 9-14 April 2010; Boston, Massachusetts.

55 Frey RW, Edwards K, Naranjo-Tackman R. Changes in CDE with laser lens fragmentation compared with standard phacoemulsification cataract surgery. *Invest Ophthalmol Vis Sci* 2010; 51:E-abstract

56 Conrad-Hengerer I, Hengerer FH, Schultz T, Dick HB. Effect of femtosecond laser fragmentation on effective phacoemulsification time in cataract surgery. *J Refract Surg* 2012;28(12):879-883

57 Nagy ZZ, Ecsedy M, Kovács I, Takács Á, Tátrai E, Somfai GM, Cabrera DeBuc D. Macular morphology assessed by optical coherence tomography image segmentation after femtosecond laser-assisted and standard cataract surgery. *J Cataract Refract Surg* 2012;38(6):941-946

58 Takács AI, Kovács I, Miháltz K, Filkorn T, Knorz MC, Nagy ZZ. Central corneal volume and endothelial cell count following femtosecond Laser-assisted refractive cataract surgery compared to conventional phacoemulsification. *J Refract Surg* 2012;28(6):387-392

59 Roberts TV, Lawless M, Bali SJ, Hodge C, Sutton G. Surgical outcomes and safety of femtosecond laser cataract surgery: a prospective study of 1500 consecutive cases. *Ophthalmology* 2013;120(2):227-233

60 Vetter JM, Holzer MP, Teping C, Weingärtner WE, Gericke A, Stoffelns B, Pfeiffer N, Sekundo W. Intraocular pressure during corneal flap preparation: comparison among four femtosecond lasers in porcine eyes. *J Refract Surg* 2011;27(6):427-433

61 Ecsedy M, Miháltz K, Kovács I, Takács A, Filkorn T, Nagy ZZ. Effect of femtosecond laser cataract surgery on the macula. *J Refract Surg* 2011;27 (10):717-722

62 Kerr NM, Abell RG, Vote BJ, Toh T'. Intraocular pressure during femtosecond laser pretreatment of cataract. *J Cataract Refract Surg* 2013; 39(3):339-342

63 Schultz T, Conrad-Hengerer I, Hengerer FH, Dick HB. Intraocular pressure variation during femtosecond laser-assisted cataract surgery using a fluid-filled interface *J Cataract Refract Surg* 2013;39(1):22-27

64 Nichamin LD. Astigmatism control. *Ophthalmol Clin North Am* 2006; 19(4):485-493

65 Rückl T, Dexl AK, Bachernegg A, Reischl V, Riha W, Ruckhofer J, Binder PS, Grabner G. Femtosecond laser-assisted intrastromal arcuate keratotomy to reduce corneal astigmatism. *J Cataract Refract Surg* 2013;39 (4):528-538

66 Nubile M, Carpineto P, Lanzini M, Calienno R, Agnifili L, Ciancaglini M, Mastropasqua L.Femtosecond laser arcuate keratotomy for the correction of high astigmatism after keratoplasty. *Ophthalmology* 2009;116 (6): 1083-1092

67 Kumar NL, Kaiserman I, Shehadeh-Mashor R, Sansanayudh W, Ritenour R, Rootman DS. IntraLase-enabled astigmatic keratotomy for post-keratoplasty astigmatism: on-axis vector analysis. *Ophthalmology* 2010;117(6):1228-1235

68 Kook D, Bühren J, Klaproth OK, Bauch AS, Derhartunian V, Kohnen T. Astigmatic keratotomy with the femtosecond laser: correction of high astigmatisms after keratoplasty. *Ophthalmologe* 2011;108(2):143-150