Femtosecond-Assisted Surgery for Keratoconus

Use of the femtosecond laser enables increased precision and reproducibility.

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Keratoconus is a noninflammatory, progressive, ectatic disease of the cornea associated with stromal thinning and irregular astigmatism. Corneal transplant surgery, such as penetrating keratoplasty (PKP) and deep anterior lamellar keratoplasty (DALK), can yield good results in patients with keratoconus. However, despite high success rates, the risks associated with DALK and, in particular, with PKP are significant and include infection, graft rejection and failure, and complications from prolonged use of topical corticosteroids.

The introduction of femtosecond lasers in ophthalmic surgery has provided the corneal surgeon with a precise tool for cutting the cornea. Femtosecond lasers use an extremely short laser pulse (1,053 nm) that causes photodisruption without damaging the surrounding tissue, with the potential to create accurate, customized cuts in many corneal planes.

Femtosecond lasers were originally introduced to ophthalmology for LASIK flap creation and have since almost completely replaced mechanical microkeratome LASIK flaps, due to greater precision and fewer complications. Now, femtosecond laser use is expanding rapidly from refractive to corneal surgery. The device’s micrometric precision cutting capabilities and its ability to create corneal cuts in multiple planes allows surgeons to design matching trephination shapes for donor and recipient corneas.

The customized corneal trephination donor-recipient shapes with the femtosecond laser include zig-zag, top-hat, mushroom, and lock-and-key. Customized corneal graft shapes should improve donor-recipient wound apposition and increase contact surface, thereby helping to achieve faster and stronger wound healing, induce less astigmatism, and result in better refractive outcomes. For severe keratoconus in particular, the ability to create such shape-matching designs for the donor and recipient increases our therapeutic surgical options for DALK and, when DALK is not possible, for PKP.

Furthermore, femtosecond lasers are being used in keratoconic eyes to create intrastromal channels for the insertion of intrastromal corneal ring segments (ICRSs), making this additive surgery safer, more accurate, and more predictable.

FEMTOSECOND LASERS FOR KERATOPLASTY

The idea of developing more stable corneal trephination with steps along the cut was conceived in the early 1950s; however, with the instruments and technology available at that time, it was simply not possible to achieve precision and reproducibility. Using suction trephines and an artificial anterior chamber, a surgical technique to manually trephine the donor and recipient corneas in a top-hat–shaped configuration was described by Busin et al in 2003. The eight cases described had faster visual recovery with earlier suture removal and reduced corneal astigmatism. Despite good early results, the complexity of the surgical technique and its lack of reproducibility prevented it from becoming popular.

In 2006, a laboratory study using human corneoscleral rings and a modified-software femtosecond laser showed not only that corneal trephination using customized shapes (such as top-hat) was feasible, fast, and safe, but also that corneal wounds were more stable and resistant to induced leakage. The first case series comparing keratoplasty performed with a conventional manual trephine versus a femtosecond zig-zag trephination was published by Farid et al. The results showed faster visual recovery with significantly less astigmatism in the femtosecond laser trephine group, but only in the early postoperative period. More recently, in another study comparing the outcomes of 50 case-controlled femtosecond laser PKPs with a zig-zag configuration versus mechanical trephination, Chamberlain et al showed similar outcomes with less topographic astigmatism in the femtosecond laser group compared with the manual trephination group, but again, only in the initial follow-up. These two studies included patients with different corneal pathologies and various indications for PKP.

The largest cohort published to date of patients who
underwent femtosecond laser-assisted PKP included 123 femtosecond laser-assisted PKPs in 119 patients. This study compared a mushroom versus a top-hat shape. Topographic astigmatism did not differ between the two groups, but the Orbscan (Bausch + Lomb) topographic irregularity index was higher in the top-hat profile than in the mushroom profile; this correlated with a statistically significant difference in the visual acuity between the two profiles that favored the mushroom-shape group. The refractive results in this large femtosecond-laser assisted PKP cohort were not superior to those following conventional trephination.

We described a novel triplanar lock-and-key femtosecond laser configuration graft shape in a laboratory ex vivo pig model. In this study, the lock-and-key shape was shown to be significantly more stable than a traditional or mushroom PKP.

There is good laboratory evidence, therefore, that femtosecond laser-customized corneal shapes are stronger than traditional straight-shaped trephine graft cuts. However, this evidence has not yet been fully translated into improved clinical outcomes.

**Femtosecond Laser Keratoplasty for Patients with Keratoconus**

Patients with keratoconus without full-thickness corneal scars are ideal candidates for DALK, which is the preferred corneal graft technique due to its well-known advantages over PKP. These advantages include lower risk of severe intraoperative complications, decreased risks of graft rejection, longer graft survival, and faster visual rehabilitation. However, when a deep Descemet central corneal scar is present (usually as a result of previous corneal hydrops), PKP may be a better option to achieve good optical results.

Visual outcomes of DALK and PKP are comparable, especially when the big-bubble technique, first described by Anwar and Teichman, is performed. This is because the big-bubble technique allows the recipient Descemet membrane to be fully exposed, removing all of the overlying corneal stroma. However, big-bubble DALK can be a challenging technique to master, with a steep learning curve.

In keratoconic eyes, femtosecond lasers have been used not only to make customized corneal trephinations but also to improve the reproducibility of the big-bubble DALK technique. Using a femtosecond laser, the surgeon can accurately cut to a very deep corneal plane, where the air needle or cannula can be more safely introduced, making the big-bubble technique more reproducible.

Buzzonetti et al published the results of a cohort of 35 patients (35 eyes) with keratoconus who underwent femtosecond laser-assisted, big-bubble, mushroom-shaped DALK. The authors described a modified technique, *IntraBubble*, in which the femtosecond laser was used to create a small and deep channel (50 µm from the endothelium), where an air cannula was introduced to create the big bubble. With this technique, the primary bubble success rate was greater than 80%.

In another series, Shehadeh-Mashor et al presented the long-term results of femtosecond laser-assisted DALK in 19 patients with corneal ectasia, most of whom had keratoconus. The authors combined the mushroom configuration with big-bubble DALK. All 19 surgeries were completed as DALK. There were three Descemet membrane perforations, but none of them required conversion to PKP. In terms of postoperative astigmatism and visual acuities, the outcomes were comparable with previously published data on manual DALK.

We reviewed the outcomes of 11 eyes with severe keratoconus that underwent femtosecond laser-assisted mushroom configuration DALK or PKP at our institution. (These results were presented in part at the Association for Research in Vision and Ophthalmology meeting earlier this year.) Recipient and donor corneas were treated with a 150-kHz femtosecond laser (IntraLase FS Laser; Abbott Medical Optics Inc.) to create a mushroom-shaped initial trephination (Figure 1). The donor’s posterior or sidecut incision was performed at a minimum depth of 80 µm from the endothelium to avoid inadvertent femtosecond laser penetration during the procedure, thereby reducing the possibility of intraoperative complications in the laser room. The mushroom recipient shape was then completed manually as a big-bubble DALK or PKP in the operating room. The donor trephination was fully cut in a mushroom shape with the femtosecond laser. Seven patients underwent DALK, with two cases converted to PKP because of intraoperative Descemet membrane perforations. Four patients underwent planned primary PKP due to preexisting full-thickness central corneal scars.

Preoperative mean BCVA was 1.26 ±0.51 logMAR, and mean central corneal thickness was 278 ±109 µm. Mean steepest keratometric (K) value was 76.0 ±9.3 D. Mean follow-up was 11 months (range, 4 to 19 months). At last follow-up, mean BCVA improved to 0.49 ±0.34 logMar, mean spherical equivalent refractive error was -3.4 ±2.92 D, and mean cylindrical refractive error was -4.1 ±3.2.

**Take-Home Message**

- The corneal surgeon can use the femtosecond laser to create matching-shaped donor and recipient corneal cuts in patients with keratoconus.
- Femtosecond laser-assisted ICRS implantation has advantages compared with manual dissection techniques, including greater safety and more reproducibility.
In our patients, femtosecond laser-assisted mushroom DALK and PKP were safe procedures with no intraoperative complications. Despite the preexisting high risk factors of our series (due to the severity of keratoconus), the technique provided good wound approximation and wound healing, yielding results comparable with those achieved in patients with less severe keratoconus. Figure 2 shows Scheimpflug images of case No. 3 of our series before and after surgery. Figure 3 shows Pentacam (Oculus Optikgeräte GmbH) images for case No. 4 before and after surgery. Figure 4 shows the slit-lamp appearance of a mushroom femtosecond laser DALK at 12 month follow-up.

ICRS IMPLANTATION

ICRSs are small, arc-shaped implants made of synthetic material that are inserted in the corneal stroma to modify corneal curvature. Colin et al.\textsuperscript{12,13} were the first to report the effectiveness of these implants for corneal ectasia. By flattening the steeper corneal axis, both refractive error and astigmatism in keratoconic eyes can be reduced.

Most studies have shown an average of 2.00 to 3.00 D of flattening, accompanied by 2 to 3 lines of gain in BCVA.\textsuperscript{12,14} However, only patients with a steepest K reading of maximum 58.00 D and corneal thickness not below 450 µm at the area planned for ICRS implantation are suitable candidates for the procedure.

The stromal channels for ICRS implantation can be created with a mechanical technique using a manual semicircular dissector or with a femtosecond laser. Because femtosecond laser energy is delivered optically to a precise depth, tunnel resections and entry incisions are more reproducible and accurate than with the mechanical method. The femtosecond laser cuts a continuous circular stromal tunnel of exact length and depth at approximately 70% of corneal depth within 15 seconds to facilitate ICRS implantation.\textsuperscript{15}

Pinero et al.\textsuperscript{16} conducted a comparative study to evaluate mechanical versus femtosecond laser-assisted ICRS procedures. No statistically significant differences were found in UCVA, BCVA, and refractive cylinder between the two groups. Although device extrusion was similar in both groups, corneal melting, neovascularization, and ring
reposition (all 4.17% [mechanical] vs 0.00% [femtosecond laser]) were present only in the mechanical arm. The ICRS implantation rate was higher in the mechanical than in the femtosecond group (20.83% vs 10.53%, respectively).16

Ertan et al17 reviewed 306 cases of keratoconus treated with ICRS implantation (Intacs; Addition Technology, Inc.). Using femtosecond laser technology to create the corneal channels, the authors reported a statistically significant improvement in UCVA and mean topographic astigmatism postoperatively. Carraquillo et al14 found no significant statistical differences in UCVA, BCVA, or manifest refraction spherical equivalent outcomes between mechanical dissection and femtosecond laser-assisted techniques to implant ICRSs in patients with keratoconus and post-LASIK ectasia. The primary advantage of femtosecond laser compared with mechanical tunnel creation for ICRS surgery is the reduction of serious intraoperative complications.17 Posterior corneal perforation is the most severe intraoperative complication of ICRS surgery,18 and its incidence is greatly reduced with use of the femtosecond laser, thereby increasing the overall safety of the procedure. Other clinical advantages of femtosecond laser technology for stromal channel creation include rapidity, precision, and ease of channel creation and centration with minimal associated stromal edema.

SUMMARY

With its ability to create accurate, customized corneal cuts, the femtosecond laser is another tool available to the corneal surgeon to further improve corneal graft surgical results in keratoconus. The ultra-precise and customized trephination possible with the femtosecond laser enables the creation of designed, matching-shaped corneal incisions with better donor-recipient fit, which should lead to improved visual rehabilitation and stronger wound resistance. Laboratory studies have shown femtosecond laser customized corneal graft incisions to be stronger than traditional incisions. Moreover, the precise cuts achieved with the femtosecond laser can help make corneal surgery, and especially Descemet DALK techniques, more reproducible.

Femtosecond laser-guided ICRS channel creation in patients with keratoconus has advantages compared with manual dissection techniques. The laser procedure is more reproducible and safer, thus reducing the complications of ICRS implantation and improving clinical results.

Although the effectiveness and cost-benefit ratio of femtosecond laser corneal graft surgery must be confirmed by further studies, there is no doubt that the femtosecond laser should be part of the modern corneal surgeon’s armamentarium, given its corneal cutting precision and capabilities.

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What do you consider to be the greatest advantage of the use of the femtosecond laser in the treatment of keratoconus?

☐ The ability to create customized corneal trephinations
☐ Increased safety of laser-guided ICRS channel creation
☐ Greater reproducibility of the big-bubble DALK technique
☐ All of the above
☐ None of the above